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AIRCRAFT SURFACE COATINGS STUDY–VERIFICATION OF SELECTED MATERIALS

ENERGY EFFICIENT TRANSPORT PROGRAM

BOEING COMMERCIAL AIRPLANE COMPANY,
P.O. BOX 3707, SEATTLE, WA 98124

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1.0 SUMMARY

A previous study of aircraft surface coatings, reported in NASA CR158954 (ref. 1), identified three liquid, spray-on elastomeric polyurethanes as best candidate materials for erosion protection and possible drag reduction. Four film/adhesive systems also were identified as candidates for application to areas of low erosion, provided that a feasible method of application to large areas could be developed. Also, flight service evaluation of two of the liquid coatings was initiated on a Continental Airlines 727 flying in the Air Micronesia route system.

The present study was confined to further investigation of the three liquid coatings, and to a lesser degree, the four films with new adhesives. The progress of the Air Micronesia flight service evaluation was monitored and results analyzed at its conclusion. Results of the laboratory investigation and the flight service evaluation are reported herein. Two additional flight service evaluations were begun late in the study, one by Delta Air Lines and the other by Continental Airlines. These airplanes currently are in service on U.S. domestic routes.

The three liquid coatings were subjected to laboratory simulations of field exposures to synthetic-type hydraulic fluid. CAAPCO B-274 was the most resistant and could tolerate most incidental brief exposures to hydraulic fluid. Chemglaze M313 showed a lower tolerance and Astrocoat Type I showed little tolerance. A topcoat of BMS 10-60 Type II polyurethane enamel over any of the three coatings provided significant additional protection against hydraulic fluid, but was less durable in areas of high erosion exposure. The dual coating systems exhibited a strong bond when subjected to adhesion and flexibility tests.

Polysulfide adhesives used to bond Tradlon, Kynar, and Kapton films to an aluminum substrate demonstrated moderate bond strengths. The highest strength, 3.27 kg/cm (18.3 lb/in) obtained with Kynar/Tra-Con 2133, was considered satisfactory for airfoil application, provided the bond strength was retained after prolonged environmental exposure.

The 14-month flight service evaluation of CAAPCO and Chemglaze accumulated nearly 3100 flight hours and over 2400 landings in the severe erosion environment of the Air Micronesia route system. No maintenance was performed on the coatings during that period. Most of the damage sustained by the coatings occurred after 2000 flight hours had been logged. Continental Airlines' evaluation of the coatings was summarized in a letter to the Contractor that is included as Appendix B to this document. The coatings showed merit sufficient that Continental agreed to participate in a second flight-service evaluation in their U.S. domestic route system.

A cost/benefits analysis was performed to provide a cursory look at airline economic considerations regarding coatings. The application of coatings to leading edges, only, for erosion protection should be done to avoid the necessity for replacement of costly eroded parts. Any drag reduction from improved leading edge smoothness, only, would not be great enough to offset coating costs by reduced fuel consumption. Using the 727 as an example, a more extensive application of coatings (leading edge to rear spar on wing and empennage) for drag reduction, must produce an airplane drag reduction of 0.3—0.5% to offset the cost of coatings. Data were not available to estimate drag benefits from coatings relative to various baseline (uncoated) surface conditions.

It is recommended that surface coating technology development be continued to the point that coatings can be offered as an option for airline fleet application. Additional testing should be performed to determine coating effects on drag, to understand their behavior in icing conditions and effects on thermal anti-icing system performance, and to ascertain that atmospheric electrical phenomena present no problems. Dual coating systems of an elastomeric polyurethane basecoat and polyurethane enamel topcoat should be explored to determine if they can provide any improvement over current systems in corrosion protection and surface smoothness.

2.0 INTRODUCTION

2.1 BACKGROUND

The study of aircraft surface coatings to reduce drag and/or maintenance costs was one of many areas investigated by NASA and industry under the Energy Efficient Transport (EET) element of the Aircraft Energy Efficiency (ACEE) program. This study was in keeping with the overall objective of the ACEE program: to improve energy efficiency of air transportation for fuel conservation.

An initial study of surface coatings under the EET contract (NAS1-14742) was reported in Reference 1. That study investigated a large number of liquid spray-on coatings and adhesively bonded films in the laboratory and found that three liquid coatings and four film/adhesive systems showed merit. The coatings were elastomeric polyurethanes: CAAPCO B-274, Chemglaze M313, and Astrocoat. The film/adhesive systems included Tradlon/PR1422, Kapton/PR1422, adhesive-backed UHMW Polyolefin, and Kynar/Adhesive 80.

A cost/benefits analysis showed that cost of coating application and maintenance could be offset, when coatings were applied back to the rear spar of wing and empennage of a 727-200, if modest drag benefits were realized.

In the Reference 1 study it was concluded that:

- Liquid spray-on coatings of the elastomeric polyurethane type were superior to other materials as a protection against rain erosion.
- Elastomeric polyurethanes are susceptible to deterioration after exposure to synthetic-type hydraulic fluid such as Skydrol or Hyjet.
- A feasible method of bonding films to large, curved surfaces is not currently known; therefore, development of liquid coating technology should be pursued with a higher priority than that for film.
- Flight and/or wind tunnel tests are necessary to measure the drag benefits from coatings.

Results of the initial study led to an extension of contract NAS1-14742 to further investigate the final three liquid coating candidates and the four film/adhesive systems emerging from the initial study, and to report on results of a flight service evaluation of CAAPCO B-274 and Chemglaze M313 that was initiated late in the study on an Air Micronesia 727.

2.2 OBJECTIVE AND SCOPE

The objective of the study extension, reported in this document, was to investigate selected surface coating materials and application processes that could lead to a net benefit to the airlines in drag reduction and/or maintenance costs. The study scope was limited to further verification of the characteristics of the final

candidate materials from the initial study, through additional laboratory testing and flight service evaluation. The study emphasis was on liquid coatings, and specifically on CAAPCO B-274, Chemglaze M313, and Astrocoat because the initial study indicated that their application to large curved surfaces was more suitable than thin films.

Much of the laboratory test effort was devoted to finding out more about the reaction of the liquid coating materials to synthetic-type hydraulic fluid (Skydrol). Tests were devised to simulate Skydrol exposures that might occur in airline operations. The tests were run on the materials alone, and with a topcoat of polyurethane enamel to provide additional protection against Skydrol. Following the Skydrol exposure tests, the specimens were evaluated for toughness, adhesion, and rain erosion. Flexibility tests of the dual coatings (topcoat of polyurethane enamel) also were run on unexposed specimens to examine their behavior under working strain.

Results of the Air Micronesia flight service evaluation were analyzed, and two additional flight service evaluations were begun. Delta Air Lines began an evaluation of CAAPCO and Chemglaze on 14 November 1979, and Continental Airlines on 20 December 1979.

NOTE:

> Certain commercial materials are identified in this paper in order to specify adequately which materials were investigated in the research effort. In no case does such identification imply recommendation or endorsement of the product by NASA or Boeing, nor does it imply that the materials are necessarily the only ones or the best ones available for the purpose.

3.0 SYMBOLS AND ABBREVIATIONS

AFB	Air Force base
AFML	Air Force Materials Laboratory
^{o}C	degree Celcius
CA	Continental Airlines
cm	centimeter
DL	Delta Air Lines
^{o}F	degree Fahrenheidt
gal/ft^2	gallon/square foot
hr	hour
in	inch
kg/cm	kilogram/centimeter
lb/in	pound/inch
LE	leading edge
LH	left hand
MEK	methyl ethyl keytone
min	minute
mm	milimeter
mph	miles per hour
m/s	meter/second
N/cm	newton/centimeter
OEW	operating empty weight
PH	pencil hardness
RH	right hand
UHMW	ultra-high molecular weight
UV	ultraviolet

4.0 STUDY RESULTS

The three most promising liquid coatings (elastomeric polyurethanes) from the Reference 1 study showed deterioration after prolonged immersion in synthetic Type IV hydraulic fluids such as Skydrol or Hyjet. Therefore, much of the laboratory effort was directed toward finding levels of coating tolerance to hydraulic fluids and ways to increase that tolerance. The four films from the Reference 1 study were tested with new adhesives, in a search for combinations with higher bond strength.

The results of a 14-month flight service evaluation of two of the coatings, CAAPCO-B-274 and Chemglaze M313, are reported. Also, two additional flight service evaluations were begun on Delta Air Lines (DL) and Continental Airlines (CA) 727s flying U.S. domestic routes. The coating applications to these two airplanes and evaluation plans are described.

A cost/benefits analysis performed during the Reference 1 study was reviewed and updated to reflect current costs of materials and flight service evaluation results.

4.1 LIQUID COATINGS

The laboratory work on liquid coatings focused on determining their compatibility with low-density, synthetic type hydraulic fluids, such as Type IV Skydrol or Hyjet, in simulated field exposure conditions. Tests were designed to duplicate conditions resulting from hydraulic system leaks and ground maintenance actions involving hydraulic fluid. Coatings topcoated with polyurethane enamel (dual coatings) were tested as a means of providing additional protection to the basecoat from Skydrol in areas of low erosion, such as aft of the front spar on wings and empennage. Also, it is possible that the dual coatings could provide good protection against corrosion in these areas, however, extensive additional testing will be required to confirm this possibility.

Hardness, adhesion and peel strength of the coatings were measured after various types and durations of exposure to Skydrol. Also, flexibility tests were performed on some of the dual coating specimens. Hardness was determined by pencil hardness tests per BMS 10-79, procedure 7.2.5 (described in Appendix A). The adhesion and peel tests were performed per References 2 and 3, respectively. Flexibility tests were done per Reference 4.

4.1.1 Laboratory Test Results

As a result of the previously demonstrated degradation of the polyurethane coatings after extended exposure to Skydrol hydraulic fluid, procedures were developed to determine the exposure limits of the coatings as well as to evaluate possible solutions to the Skydrol problem. Laboratory setups were developed to simulate hydraulic fluid leakage from within the confines of the wing and other exposure conditions that might be expected under flight or field maintenance operations. Coating hardness and peel-strength measurements were performed after hydraulic fluid exposure.

DeSoto BMS10-60 Type II white polyurethane enamel is resistant to Skydrol and was evaluated as a topcoat over CAAPCO B-274, Chemglaze M313 and Astrocoat (MIL-C-83231, Type I). Flexibility and wet tape adhesion tests were run to

evaluate the integrity of the dual coating systems. The promising coating systems that emerged from the fluid exposure tests were subjected to rain erosion tests at the Air Force Materials Laboratory (AFML) rain erosion facility at Wright-Patterson AFB. Although rain erosion performance is most critical for coatings selected for leading-edge application, the rain erosion performance also provides a durability evaluation of materials subjected to Skydrol spillage. A matrix of the tests performed is included as Table 1.

Table 1. Liquid-Coating Test Matrix

	Coating systems						
	1	2 (dual)	3	4 (dual)	5	6 (dual)	7
Laboratory tests	CAAPCO B-274	CAAPCO B-274 and BMS 10-60, Type II	Chemglaze M313	Chemglaze M313 and BMS 10-60, Type II	Astrocoat, MIL-C-83231, Type I	Astrocoat, MIL-C-83231, Type I and BMS 10-60, Type II	BMS 10-60, Type II
<u>Skydrol puddling</u>	X	X	X	X	X	X	X
Hardness per BMS 10-79 Procedure 7.2.5	X	X	X	X	X	X	X
<u>Skydrol drip</u>	X	X	X	X	X	X	
Hardness per BMS 10-79, Procedure 7.2.5	X	X	X	X	X	X	
Adhesion test per FED-STD-141a Method 6301.1	X	X	X	X	X	X	
<u>Skydrol spillage</u>	X	X	X	X	X	X	
Hardness per BMS 10-79 Procedure 7.2.5	X	X	X	X	X	X	
<u>Skydrol immersion</u>							
• 7 days		X		X		X	X
• 30 days		X		X		X	X
• To limit of coating capability	X	X		X		X	
Hardness per BMS 10-79, Procedure 7.2.5	X	X	X	X	X	X	
Peel strength per ASTM D903	X	X	X	X	X	X	
Rain erosion: 179 m/s (400 mph)	X	X		X		X	
Rain erosion: 224 m/s (500 mph)	X	X		X		X	
Flexibility per FED-STD-141a, Method 6221		X		X		X	
Wet tape adhesion per FED-STD-141a, Method 6301.1		X		X		X	

Primer Application Studies—In preparation for the Skydrol exposure tests, primer application studies were performed to determine the adhesion of the polyurethane coatings to clad 2024-T3 aluminum. DeSoto BMS10-79 Type II, Hughson 9924, and Products Research PR 1432-GP primers were subjected to peel-strength measurements using CAAPCO B-274. Variations evaluated with BMS10-79 and 9924 were cure time and primer surface roughness. The primer surface was roughened by hand sanding. Variations were not attempted with the PR 1432-GP primer due to the poor peel-strength performance in the initial tests. The surface preparation consisted of abrasion (Scotchbrite) and alkaline cleaning (Alkanox) followed by an alodine process.

The results, which are summarized in Table 2, showed that primer curing time is important for BMS10-79 and also that this primer provided the best adhesion strength. In four of the seven peel tests (with BMS10-79), peeling could not be initiated, whereas all of the peel tests with 9924 and PR 1432-GP primers resulted in adhesion failures between the primer and coating and also between primer and substrate. The BMS10-79 Type II primer was then selected for all of the Skydrol exposure test specimens, and the curing time prior to overcoating was specified as 3 hours.

Specimen Preparation—The substrate material used in the coating evaluation tests was 2024-T3 alclad aluminum. The procedure for preparing the substrate consisted of cleaning with an abrasive pad (Scotchbrite) and an alkaline solution (Alkanox). The cleaned, rinsed, and dried surface was alodined with Alodine 1200. The substrate was primed with 0.025 mm (1 mil) of DeSoto BMS10-79 Type II primer and 0.254 to 0.356 mm (10 to 14 mils) of surface coating material was applied. On topcoated specimens, a 0.036 to 0.046 mm (1.4 to 1.8 mil) thickness of DeSoto

Table 2. Primer Application Studies

Primer	Primer cure conditions	180-deg peel strength, (ASTM D903), N/cm	(lb/in)	Remarks
Hughson 9924	Overnight and sanded	1.59	(8.9)	Adhesion failure, primer/topcoat
	Overnight	1.46	(8.2)	Adhesion failure
	30 min	1.45	(8.1)	Adhesion failure
	1 hr	1.39	(7.8)	Adhesion failure
	2 hr	1.54	(8.6)	Adhesion failure
BMS 10-79	Overnight and sanded	1.46	(8.2)	Adhesion failure
	Overnight	1.54	(8.6)	Free film broke after peeling started, adhesion failure
	Oven cure 10 min at 93.3°C (200°F) + overnight cure	1.61	(9.0)	Adhesion failure
	30 min	1.48	(8.3)	No peeling, cohesion failure
	1 hr	1.91	(10.7)	No peeling, cohesion failure
	2 hr	2.18	(12.2)	No peeling, cohesion failure
	3 hr	2.59	(14.5)	No peeling, cohesion failure
PR-1432-GP	3 hr	0.77 0.13	(4.3) (0.7)	Adhesion failure, primer/substrate and primer/topcoat

Notes:

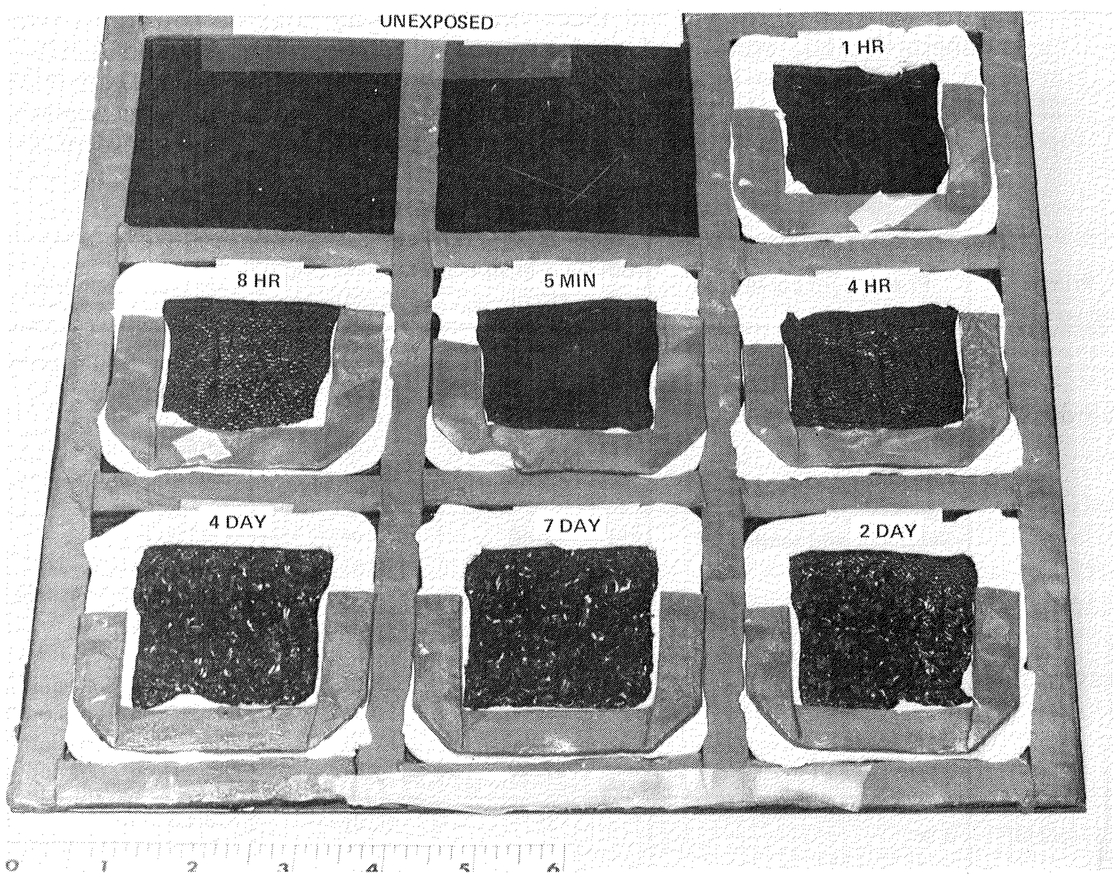
- Substrate abraided with Scotchbrite and cleaned with Alkanox.
- Primer coated with CAAPCO B-274.

BMS10-60 polyurethane enamel was applied. All of the test specimens were cured for a minimum of 7 days at room temperature prior to fluid exposure. A listing of the coating materials subjected to the hydraulic fluid exposure tests is as follows:

Coating system	Description
1	CAAPCO B-274
2 (dual)	CAAPCO B-274 plus BMS10-60
3	Chemglaze M313
4 (dual)	Chemglaze M313 plus BMS10-60
5	Astrocoat Type I per MIL-C-83231
6 (dual)	Astrocoat Type I plus BMS10-60
7	BMS10-60

4.1.1.1 Skydrol Exposure Tests

Tests were performed to identify the exposure time limits of each polyurethane coating to deterioration from Skydrol. The tests were accomplished on coated 30.5 x 30.5 cm (12 x 12 in) aluminum panels, which were subdivided by means of zinc chromate tape to create multiple test sections for various exposure times. Figure 1 shows a subdivided panel used in Skydrol puddling tests. The hydraulic fluid was kept away from the edges of the panel to eliminate coating deterioration conditions along the edges.

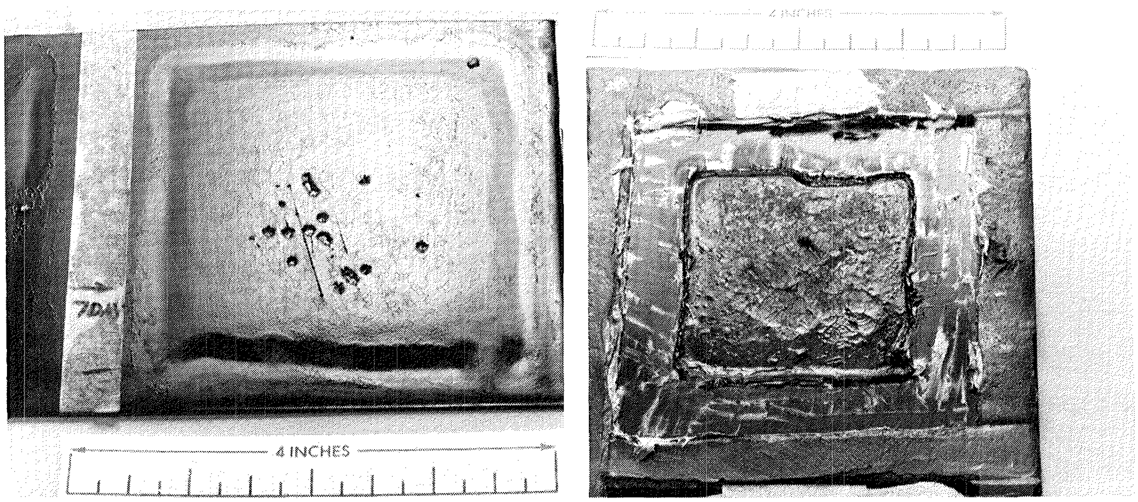


● Progressive degradation of Astrocoat with increasing exposure time

Figure 1. Panel Configuration for Skydrol Puddling Tests

Puddling Tests—The test specimens were subjected to a 0.32-cm (0.125-in) fluid head for periods varying from 5 minutes to 7 days, at which time the fluid was removed using an eye dropper. Following exposure, each section, plus an unexposed section, was subjected to pencil hardness recovery tests in accordance with BMS10-79 Procedure 7.2.5. Pencil hardness tests were performed immediately following the exposure and over the ensuing 5-week period. After completion of the recovery tests, the fluid film was washed off and coating adhesion tape tests were performed in accordance with Federal Test Method Standard 141a, Method 6301.1 (ref. 2).

The hydraulic fluid puddling tests are summarized in Table A-1 of Appendix A. Chemglaze M313 (coating No. 3) and Astrocoat (coating No. 5) were severely attacked after 5 minutes of exposure. All other coatings survived the 7-day fluid puddling but experienced a reduction in pencil hardness after most exposure periods, relative to the unexposed baseline. Coating No. 1 exhibited swelling. Panels topcoated with BMS10-60 did not exhibit visual evidence of deterioration. Coating No. 7 (BMS10-60 polyurethane enamel only) was included as a reference specimen. The post-test conditions of coatings No. 1 and 3 are shown in Figure 2 and that of coating No. 5 is shown in Figure 1.



- Coating swollen
- Coating scratched and punctured by pencils during hardness testing

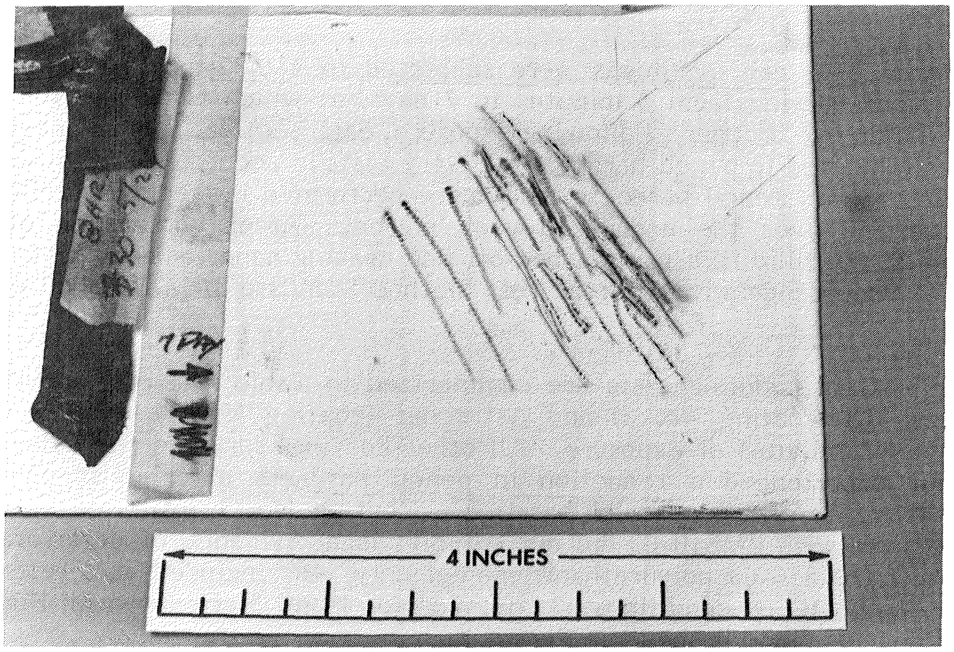
- Severe deterioration

a. **Coating No. 1 (CAAPCO) after 7 days of exposure**

b. **Coating No. 3 (Chemglaze) after 1 hr of exposure**

Figure 2. Puddling Test Specimens After Skydrol Exposure

Dual coating No. 2 was the most fluid resistant, followed by No. 4 and 6. Coating No. 2 was harder, No. 4 was approximately equivalent, and No. 6 was softer than the reference coating (No. 7) in post-exposure pencil-hardness measurements. The hardness measurements showed that none of the coatings recovered after Skydrol exposure, but a stabilizing trend is indicated for BMS10-60 coated candidates after the 7-day exposure. A typical dual-coated test specimen is shown in Figure 3. The baseline (unexposed) specimens of coatings No. 2, 4, and 6 exhibited a reduction in pencil hardness as a result of aging but no visual evidence of change.



- Coating scratched by pencil hardness test
- Scribe marks in upper right panel area are tape adhesion test boundaries

Figure 3. Dual Coating No. 2 After 7-Day Skydrol Exposure (Also Typical of Coatings 4 and 6)

Tape tests were conducted to determine if the coatings retained their adhesion to the aluminum substrate after hydraulic fluid exposure. Tests were run only on specimens that were not severely attacked by hydraulic fluid. The specimens to be tested were cleaned with a detergent and an adhesive tape was applied. The tape was pulled at 90 deg to the test panel to evaluate the coating-substrate bond. Some of the tests were invalid because the tape did not adhere well to the coating, indicating penetration of the hydraulic fluid into the coating. Of the remaining valid tape tests, no coating-substrate adhesion failures were encountered.

As shown in Table A-1 of Appendix A, all baseline (unexposed) specimens passed the tape test. Also, all exposed dual coating specimens and coating No. 7 passed the test. The remaining specimens of coatings No. 1, 3 and 5 (single-coated) either were not tested or the tests were invalid because of poor tape adhesion to the coating specimen.

Spillage Tests—Tests were performed to simulate the effects of hydraulic fluid spillage on the upper-wing or leading-edge surfaces during field maintenance. These tests were accomplished by pouring Skydrol on 30.5 x 30.5 cm (12 x 12 in) panels and allowing the fluid to run off. The test panels were subdivided into multiple test areas to allow for variations in wipe off times. After fluid spillage, the residual film of fluid was allowed to air dry for periods from 5 minutes to 7 days (corresponding to the Skydrol puddling test periods) prior to being wiped off with a lint-free cotton cloth. Thus, a direct comparison of results with the Skydrol puddling tests could be made. After fluid wipings, each test area, plus an unexposed baseline test area, was subjected to pencil hardness recovery tests over a 5-week period of time. The test specimens were then detergent cleaned and subjected to coating adhesion tape tests as previously described.

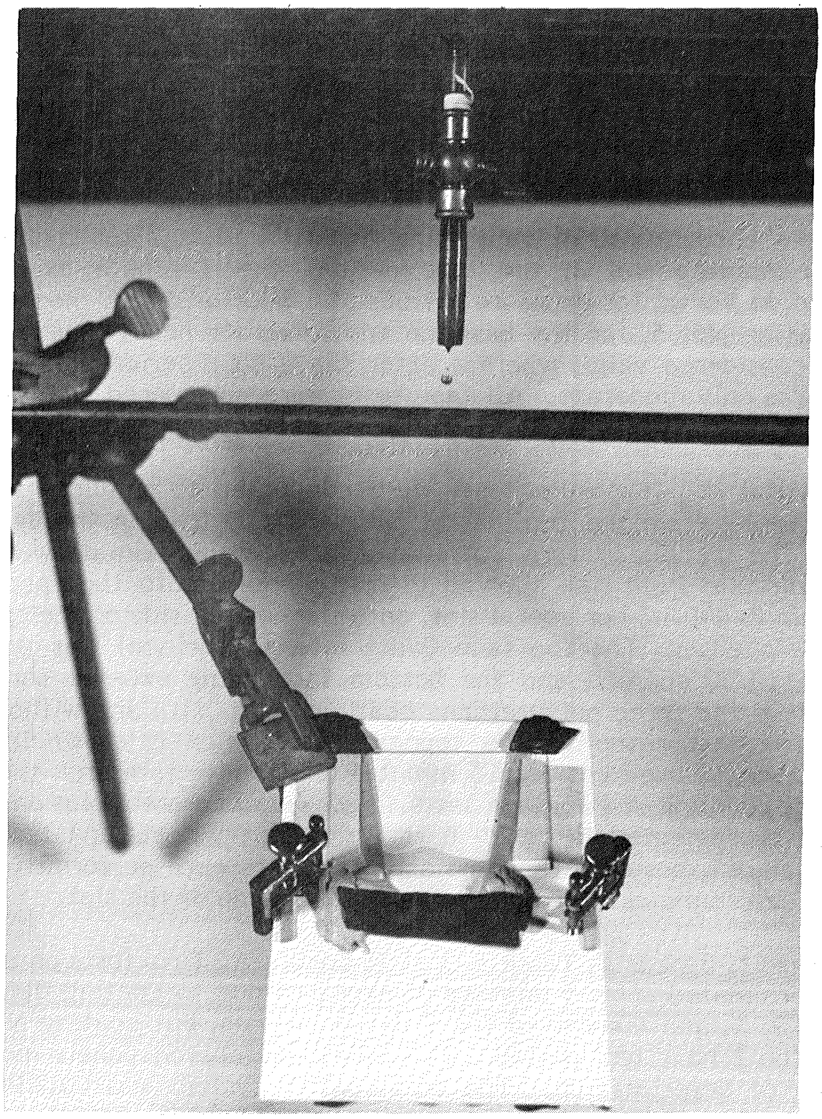
The test results are shown in Table A-2 of Appendix A. Coating No. 3 and 5 were attacked after 5 minutes, although not as severely as in the Skydrol puddling tests. Beyond the 8-hour wipe-off period, coating No. 1 became difficult to wipe, developed a matted appearance, and tended to smear. Panels coated with an overcoating of BMS10-60 (No. 2, 4 and 6) did not exhibit visual deterioration. Dual coating No. 2 was the superior material, followed by No. 4 and 6. The post-exposure hardness of No. 2 was approximately equivalent to the reference coating (No. 7), whereas dual coatings No. 4 and 6 were softer. Baseline areas of BMS10-60 coated panels exhibited a reduction in hardness after aging.

No failures were encountered in valid tape adhesion tests after hydraulic fluid exposure. For coating No. 3, the baseline and the 5-minute exposure were considered valid, however, for exposure periods of 1-hour or more, the test was not valid. On coating No. 5, for the baseline and 5-minute and 1-hour periods, the tape test was considered valid, whereas after the 4-hour period and beyond, the tape adhesion was only moderate. All tape tests were considered valid on coatings No. 1, 2, 4, 6, and 7.

Drip Tests—Skydrol drip exposure tests were conducted to simulate a hydraulic fluid leak originating from the confines of the wing and leaking through joints in the structure. The specimens were slotted and inclined approximately 30 deg from horizontal. Hydraulic fluid was allowed to drip steadily onto the specimen and, through a 0.1-cm (0.040-in) horizontal slot, onto the bottom side of the specimen to run off the lower edge. The top face (wing interior surface) was coated with primer and BMS10-60 enamel, and the bottom face (wing exterior surface) with primer and each of the three polyurethane coatings, both with and without BMS10-60 topcoat. The test setup with a topcoated specimen is shown in Figure 4. Exposure times were varied between 5 minutes and 7 days to match the exposure times of Skydrol puddling and spillage tests. Each exposed area, plus an unexposed baseline area, was subjected to pencil hardness recovery tests and tape adhesion tests following fluid exposure. The tape adhesion tests were performed across the slotted area to determine coating adhesion along the edge of the slot.

The drip test results appear in Table A-3 of Appendix A. Drip tests on coating No. 3 and 5 were terminated after 5 minutes of exposure due to coating deterioration. Coating No. 1, 2, 4, and 6 survived the 7-day drip tests, but coating No. 1 began swelling after the 8-hour test period. The BMS10-60 coated panels did not show visual evidence of deterioration. The best coating system was CAAPCO B-274, followed by Chemglaze M313 and Astrocoat, all topcoated with BMS10-60.

The Skydrol drip tests appeared to be more severe than either the Skydrol puddling or spillage tests, as evidenced by the post-exposure pencil hardness values, which were lower than for either of the other two test series. This may be attributed to the continuous flow of liquid across the specimen. In the puddling and spillage tests, a stagnant fluid film at the coating surface was generated, which provided some measure of insulation against fluid penetration into the coating. The initial post-test pencil hardness measurements were performed on surfaces that had been wiped dry. Differences in pencil hardness values performed on wet versus dry surfaces were not large, but as in the other Skydrol exposure tests, the pencil hardness measurements demonstrated that the coatings did not recover. The baseline specimens of each coating also exhibited a reduction in pencil hardness with aging, as seen on other test panels.



● Dam and glass cover used to obtain continuous distribution of fluid across slot

Figure 4. Skydrol Drip Test Setup

Post-exposure tape adhesion tests on coating No. 1, 2, 4, and 6 were considered to be valid since there was good adhesion of the tape after detergent washing of the coating surface. On coating No. 3 and 5, the tape adhesion tests were considered to be invalid due to poor adhesion of the tape after detergent washing of the coating surface.

Immersion Tests—Skydrol immersion tests, followed by peel strength tests, were conducted on coating No. 1, 2, 4, and 6. Coating No. 3 and 5 were not evaluated due to their poor resistance to Skydrol demonstrated in previous tests. Exposure times were selected on the basis of previous performance in the Skydrol puddling, spillage, and drip tests. Coating No. 1 was immersed for 2 days and coating No. 2, 4, and 6 for 7 days, and also for extended periods until the coatings showed evidence of deterioration. At the end of each immersion period, the specimens

were subjected to pencil hardness tests and to peel tests per ASTM 903 (Reference 3). Per ASTM 903, the adhered portion of the coating was immersed, whereas the free film portion was left unexposed to maintain its integrity for the 180-deg peel tests.

Results of the immersion tests are shown in Appendix A, Tables A-4 and A-5. Coating No. 1 survived the 2-day immersion test but exhibited some swelling. Dual coatings No. 2, 4, and 6 survived the 7 days of hydraulic fluid immersion without visual evidence of deterioration. The peel strength of coating No. 4 could not be obtained due to unexpected adhesion of the free film to the substrate, which prevented any peel strength measurements. On coating No. 1, the free film was sufficiently weakened adjacent to the bonded area to prevent recording of the peel strength. Dual coatings No. 2 and 6 exhibited cohesive failures in the free film, indicating that the coating adhesion was greater than the free-film strength. Post-test pencil hardness measurements taken after blotting the surface dry indicated softening equal to, or greater than had been experienced in the Skydrol drip tests.

The extended-duration immersion tests on dual coatings No. 2, 4, and 6 demonstrated the exposure limits of these materials to Skydrol without significant surface deterioration or loss of adhesion. Dual coating No. 2 survived 30 days, No. 4 survived 16 days, and No. 6 survived 14 days. Specimens were removed from the fluid when the surface showed evidence of deterioration as indicated by a uniform appearance of shriveling similar to fingerprint patterns. In the post-immersion peel tests, the three coatings exhibited better adhesion than the free-film strength.

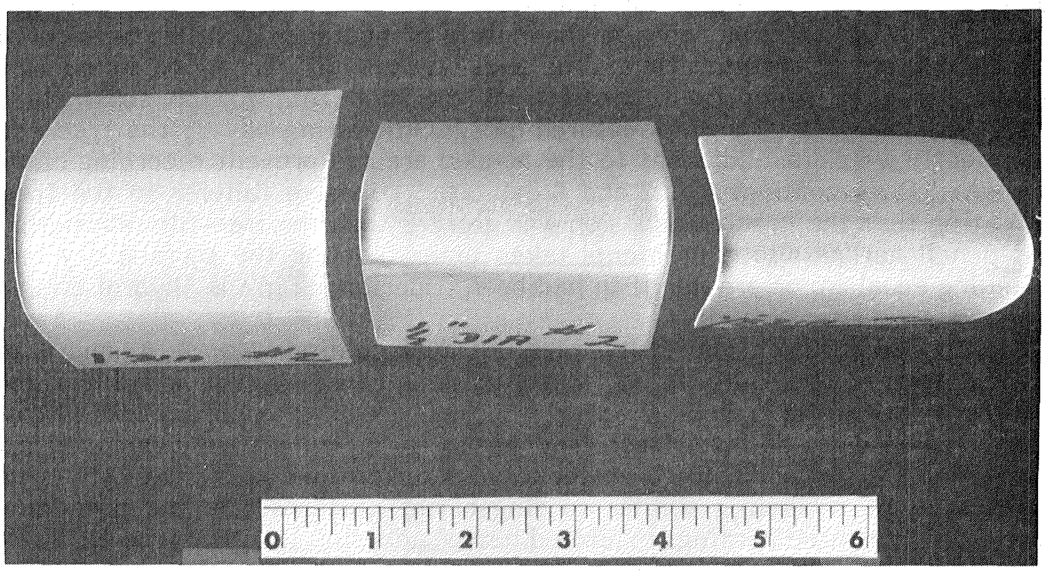
4.1.1.2 Coating Characteristics Tests

Baseline Pencil Hardness—During the fluid exposure tests (described in Appendix A), it was observed that the pencil hardness of baseline (unexposed) dual coatings decreased with age. Therefore, pencil-hardness measurements as described in Appendix A were continued over a period of 6 months to monitor this condition. The pencil-hardness values for the baseline coatings listed in Appendix A, Table A-6 were shown to stabilize after 2 to 3 months and subsequently did not change. The topcoated materials had initial hardness values above the BMS10-60 reference material (No. 7) then stabilized at values slightly lower in hardness than the reference material. This lower hardness may have been due to solvent or volatile entrapment beneath the topcoat and did not appear to be detrimental. Excellent adhesion of the basecoat to the substrate and to the topcoat were demonstrated in flexibility and tape adhesion tests.

Wet Tape Adhesion—Wet tape adhesion tests were performed on the dual coatings (No. 2, 4, and 6) to evaluate intercoat adhesion. The tests were performed in accordance with Federal Standard 141a, Method 6301.1 (ref. 2) after 24-hour immersion of the tape in distilled water. The edges of the test panels were sealed to prevent edge deterioration while under immersion. All three coatings passed the wet tape adhesion test without visual evidence of deterioration or delamination. Coating hardness did not change appreciably as indicated by the pre- and post-test pencil hardness measurements listed below.

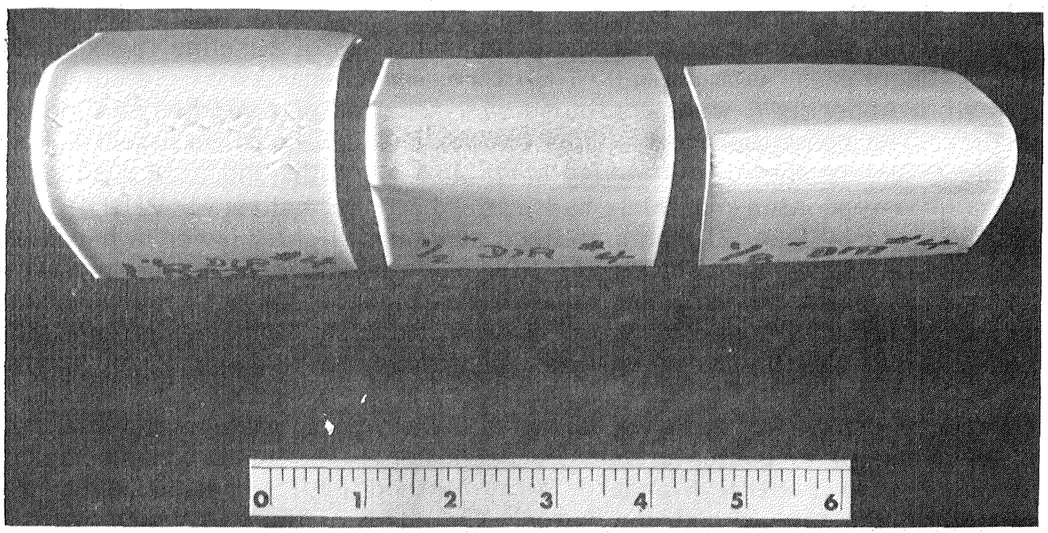
	Pencil hardness	
Dual-coating number	Before soak	After soak
2	F	H
4	4B	4B
6	B	2B

Flexibility—Flexibility tests also were conducted on dual coatings No. 2, 4, and 6. The tests were performed in accordance with Federal Test Standard 141a, Method 6221 (ref. 4) using 0.32 cm (0.125 in), 1.27 cm (0.5 in), and 2.54 cm (1.0 in) diameter mandrels. All three coatings passed the test. Coating No. 2 showed no evidence of delamination or surface irregularities. Coating No. 4 and 6 developed waffle-type stress marks beneath the topcoat that were most pronounced at the minimum bend radius. Figure 5 shows flexibility test specimens of coating No. 2 and 4.



● No stress marks or delamination

a. Coating No. 2 (CAAPCO plus enamel)



● Stress marks developed in basecoat

b. Coating No. 4 (Chemglaze plus enamel)

Figure 5. Flexibility Test Results

Rain Erosion—Rain erosion performance was measured on the coating systems that demonstrated Skydrol resistance in the fluid exposure tests. These included coating No. 1, 2, 4, and 6. Test specimens, except for coating No. 1, were subjected to hydraulic fluid spillage exposure and wipe-off after 7 days. Coating

No. 1, the only rain erosion coating without topcoat to exhibit resistance to Skydrol, was wiped off after 2 days, a period that represented the practical limit of resistance to Skydrol for this material.

Rain erosion tests* were run at 179- and 224-m/s (400- and 500-mph) speeds in a rainfield of 1.8 mm (0.071 in) diameter droplets falling at a rate of 2.54 cm (1.0 in) per hour. Two specimens of each coating mounted at the extremities of the rotating arm were run at each condition. The substrates were the standard airfoil-shaped 6.1-cm (2.4-in) long aluminum specimens normally used by AFML. Exposed and unexposed specimens of each coating were run, and penetration times through the topcoat and basecoat recorded. A television camera, monitor, and strobe unit enabled the operator to observe the mode of failure and time to failure of specimens while the apparatus was running. The test was terminated when either or both specimens mounted on the rotating arm failed or reached a test time of 180 minutes. The rain erosion test results are included as Tables A-7 and A-8 in Appendix A. The penetration times represent erosion of a localized spot in the coating where the underlying surface first appeared. Other columns list the progressive degradation time as a percentage estimate of the total eroded area (when observed) total time, and the post-test condition of the specimens. The significant findings of the rain erosion test series are discussed below.

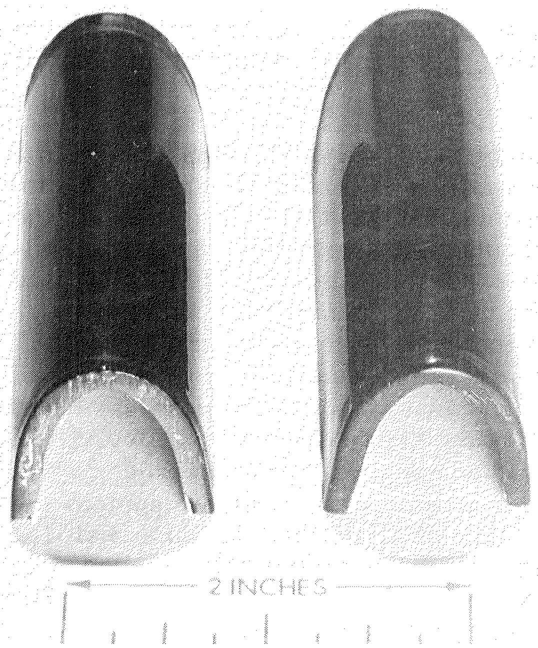
The BMS10-60 topcoat used in dual coatings No. 2, 4, and 6 did not offer significant rain erosion resistance, particularly at 224 m/s (500 mph) where deterioration began in less than 10 minutes. This was not unexpected since the topcoat was applied as a thin 0.038-mm (1.5-mil) layer.

The presence of BMS10-60 topcoat on CAAPCO B274 (dual coating No. 2) appeared to degrade the rain erosion resistance of the basecoat. At 179 m/s (400 mph) there was no erosion (exposed or unexposed) of B-274 after 3 hours, whereas with the topcoated specimens, the basecoat began to deteriorate at 98 to 113 minutes. At 224 m/s (500 mph), the differences with and without topcoat were not as discernible since two of the specimens without topcoat suffered damage at 43 to 73 minutes. The difference in rain erosion performance between exposed and unexposed B-274 coatings either with, or without, topcoat was not significant. The exposed specimens showed a slight trend toward better performance based upon penetration times and post-test appearance (fig. 6a).

Chemglaze M313 provided the best rain erosion performance of the three top-coated candidates in this test series. Its performance after exposure to 7-day Skydrol spillage approached that of the B-274 without topcoat. Specimens subjected to 7-day Skydrol spillage exhibited substantially better rain erosion resistance than the unexposed specimens, as indicated by the condition of the post-test specimens in Figure 6b. The reason for the performance improvement after Skydrol exposure is unclear, except that Skydrol fluid may have penetrated the surface and plasticized the coating, which resulted in increased flexibility. It was also noted that the basecoat surface of the exposed specimens was less damaged and somewhat smoother than for the unexposed specimens.

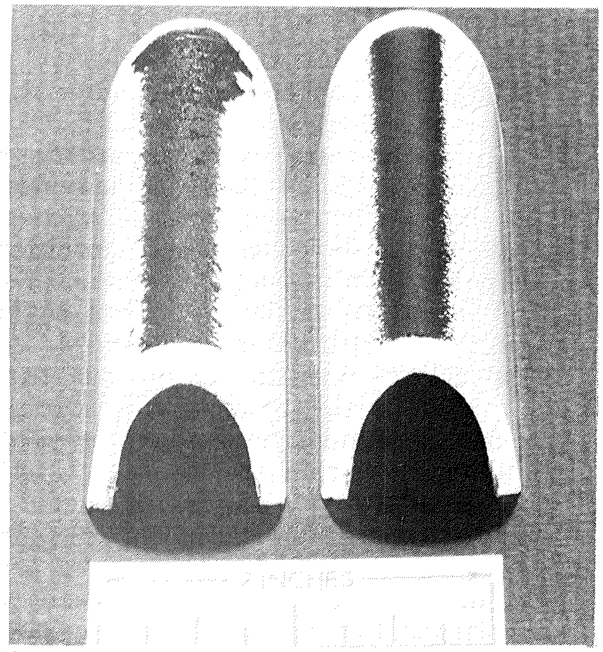
The rain erosion performance of Astrocoat was characterized by peeling, as shown in the right hand specimen in Figure 6c. Peeling appeared to start at the nose of the specimens and propagate toward the rear beyond the normal erosion area.

*The rain erosion tests were performed at the AFML rain erosion facility in Dayton, Ohio.



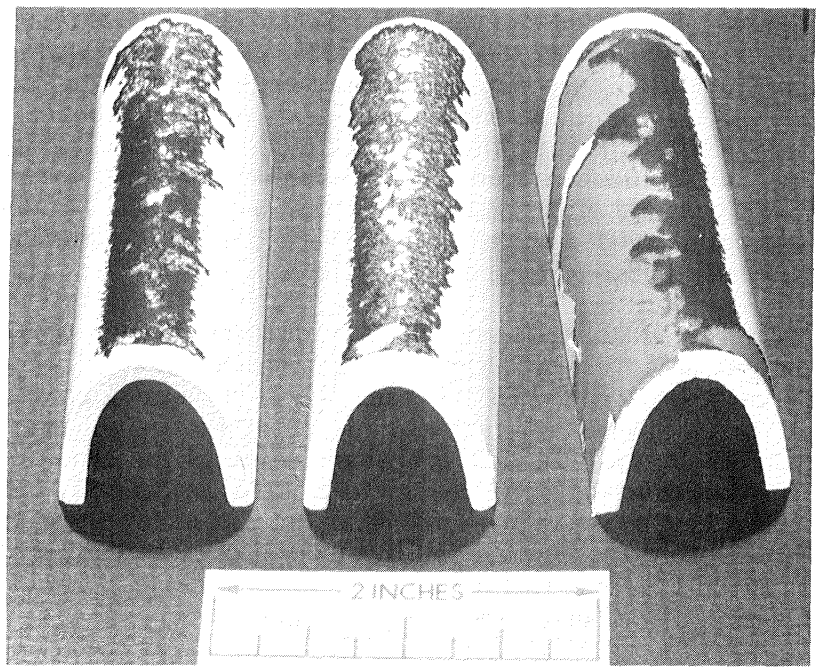
- Test duration—3 hr
- Left specimen
  - Unexposed
- Right specimen
  - 2-day Skydrol exposure

a. Coating No. 1 (CAAPCO) after 224-m/s (500-mph) test



- Left specimen
  - Unexposed
  - Test duration—2.5 hr
- Right specimen
  - 7-day Skydrol exposure
  - Test duration—3 hr

b. Coating No. 4 (Chemglaze plus enamel) after 179-m/s (400-mph) test



- Left and center specimens—nonuniform erosion patterns
- Right specimen—peeling and delamination

c. Typical dual-coating failure modes

Figure 6. Rain Erosion Test Results

Peeling was either down to the primer or within the basecoat, thereby giving the appearance of delamination. Despite the peeling, the basecoat exhibited high penetration times before the primer became exposed. The 179-m/s (400-mph) data for unexposed Astrocoat may not be representative of the performance of the material since the specimens were inadvertently run at 224 m/s (500 mph) until the topcoat began to erode. Astrocoat specimens exposed to 7-day Skydrol spillage exhibited better rain erosion resistance than unexposed specimens, which is consistent with the rain erosion performance of Chemglaze M313.

4.1.2 Application Process

Aluminum-Surface Preparation—Aluminum surfaces (except new anodized surfaces) are cleaned with an abrasive pad such as Scotchbrite or Doodlebug, the latter being less abrasive than Scotchbrite. This is followed by cleaning with an alkaline cleaner such as Alkanox. The cleaned surface is then alodined and primed with 0.013 mm (0.5 mil) to 0.020 mm (0.8 mil) of BMS10-79 Type II primer. MIL-P-23377 primer also is acceptable. Surface cleaning and alodine application should be done prior to masking to eliminate poor coating adhesion along the edges of the tape. It is advisable to extend the primed area about 0.32 cm (0.125 in) beyond the coated area, where masking is required, to obtain the best possible coating adhesion along the masked edges.

CAAPCO B-274—B-274 is a three-component, nonmoisture curing polyurethane coating. It requires nine to twelve applications of one to two crosscoats at 10- to 30-minute intervals (for solvent evaporation) to achieve 0.254 to 0.356 mm (10 to 14 mils) of coating. The material is characteristically translucent until several mils (>7) of the material are applied. Thinning to a spray viscosity of 25 to 28 Zahn No. 2 (a viscosity such that a Zahn No. 2 cup will drain in 25 to 28 seconds) with the thinner provided by CAAPCO is required to prevent air entrapment during application. Care must be exercised to prevent sagging. Application at temperatures less than 21°C (70°F) is not recommended. The material has a 4-hour pot life. Coverage of 0.254 to 0.305 mm (10 to 12 mils) requires 1.24 ℓ/m^2 (0.03 gal/ft^2). Priming 2 to 5 hours prior to the coating application is recommended for maximum adhesion. Post-curing of 2 to 3 days at room temperature is recommended, but can be accelerated by heating to 66°C (150°F) for 3 hours after an initial room temperature cure for 24 hours. Minimal experience is required to apply the coating. The only equipment required is a standard suction cup spray gun. Adequate ventilation is critical, however, due to the flammable solvents contained in the coating system.

Chemglaze M313—M313 is a two-component, nonmoisture curing polyurethane coating. It requires three to five applications of three to four crosscoats at 1- to 2-hour intervals (for solvent evaporation) to achieve 0.254 to 0.305 mm (10 to 12 mils) of coating. This material is not as translucent, nor is the viscosity as low, as the CAAPCO B-274. Control of humidity is not required during application, but the curing agent by itself is extremely moisture sensitive. Only sufficient Chemglaze for each application should be activated at any time. Application at temperatures less than 21°C (70°F) is not recommended. The activated vehicle has a 2-hour pot life. Application of 10 to 12 mils requires 1.24 ℓ/m^2 (0.03 gals/ft^2). Priming 2 to 5 hours prior to the coating application is recommended for maximum adhesion. Post-curing of 3 to 5 days at room temperature is recommended, but can be accelerated by baking for 2 hours at 93 to 124°C (200 to 225°F) after room

temperature solvent evaporation of at least 2 hours. No special training or equipment is required for application, only the use of a suction cup spray gun. The spray process must be performed with adequate ventilation.

Astrocoat Type I—This catalyst-activated, moisture-curing polyurethane coating requires approximately 12 applications at 1-hour intervals to achieve 0.254 to 0.305 mm (10 to 12 mils) of coating. Control of humidity and temperature is necessary for proper application. A minimum of 50% relative humidity at 21°C (70°F) is needed for coating cure. Severe bubbling will occur if each coat is not cured before the next coat is applied. Force curing at high humidity (70%) between coats allows the time interval between coats to be reduced to 45 minutes. Post-curing of 3 to 7 days is recommended. A wash primer is included in each kit, however, Astrocoat is compatible with epoxy-type primers. Coating tends to have an "orange peel" appearance and the coating application requires a master-level painter. Priming 2 to 18 hours before application is acceptable if the Astrocoat kit primer is used. The spray application must be performed with adequate ventilation, as flammable solvents are contained in the coating system.

4.1.3 Repair and Maintenance

The feasibility of stripping and repair were evaluated on small-scale specimens in the laboratory. Preliminary procedures were developed for localized repair of simulated nicks or pitting, and for major repair where complete removal down to the base metal was required. The specimen preparation procedures used in the coating, stripping, and repair experiments were limited to B-274 and M313 materials.

4.1.3.1 Stripping

Experiments were performed to determine the strippability of B-274, M313, and Astrocoat, with and without BMS10-60 topcoat. Turco 5351 was used as a stripping agent. All of the coatings were strippable, but with varying amounts of difficulty. The BMS10-60 topcoat had a negligible impact on the strippability of the three primary coatings. Astrocoat was easily loosened from the metal substrate in 1.5 to 2 hours with one heavy application of the stripping agent, followed by scraping with a plastic scraper. M313 was loosened within 3 to 4 hours, following the same procedure. B-274 required an overnight soak of the stripping agent to loosen the coating. Repeat heavy applications (two or three) of stripping compound, with 1-hour soak and scraping in between, was required to completely remove the primer. The alodined surface remained intact in the stripping evaluations.

4.1.3.2 Repair Procedures

Minor Repair—A procedure for minor repairs, limited to nicks or gouges where bare metal has not been exposed, is itemized below:

- Apply masking around the repair area approximately 2.54 cm (1 in) outside of the damaged area.
- Sand the damaged area with 180 grit or finer abrasive.
- Avoid sanding to expose metal.

- Remove sanding residue with a cheesecloth moistened with solvent such as methyl ethyl keytone (MEK), then wipe the surface dry with a clean cheesecloth.

- Reapply coating by filling damaged cavity using a soaked cotton swab (Q-Tip).

- Apply only enough coating material to avoid sagging. The coating should not be thinned for repair applications.

- Level the coating with a sharp straight edge (such as a razor blade) using the edges of the damaged area as a guide. Multiple applications may be necessary depending upon the amount of build-up required.

- Allow the coating to become tacky between applications. The B-274 becomes tacky in 15 to 30 minutes, and the M313, in 1 to 2 hours.

- If the installation is topcoated with BMS10-60, remove any smearing of black polyurethane by wiping the topcoat with cheesecloth moistened with MEK.

- Allow the basecoat to become tack free (1 to 2 hours) prior to application of the topcoat.

- The BMS10-60 topcoat can be applied using a good quality natural bristle brush.

- Apply material in one direction as much as practicable, using light pressure on the brush to form an even, continuous film. Apply only enough material to cover the basecoat.

- Cure per manufacturer's instructions.

Major Repair—The procedure for major repair is as follows:

- Apply masking around the repair area.

- Extend repair area to natural boundaries (edges), where practicable, to minimize the length of coating boundaries. Coating boundaries require more attention than the remainder of the repair.

- Orient masking chordwise or parallel to natural edges to simplify repair area.

- Strip the repair area down to the base metal, using heavy brush applications of Turco 5351 stripping compound. Keep the stripping compound away from edges of masking tape to prevent migration of the stripping agent beneath the tape. The activation time of the primer will vary as described in paragraph 4.1.3.1.

- Scrape loose material off with a plastic or teflon scraper.

- Reapplications of stripping compound may be required to completely remove the primer.

- Scrape the boundaries of the repair area until loose coating has been removed and a firm edge established in the old coating.

- Sand an approximately 0.64-cm (0.25-in) wide transition zone (to roughen surface) surrounding the repair area, using 180-grit sandpaper. Feather edging is not required. Avoid sanding exposed metal.
- Remove masking and solvent wipe the repair area with MEK.
- Wipe surface dry with a clean cheesecloth.
- Mask area surrounding repair for coating application.
- Install 2.54-cm (1.0-in) wide metal coupon immediately adjacent to repair area for coating thickness measurements.
- Apply BMS10-79 primer, using spray gun (just enough to cover the exposed metal surface) and allow to cure for 2 to 5 hours.
- Perform spray gun application of coatings as described in 4.1.2.
- Slowly remove masking while coating is wet, exercising care to prevent ragged edges.
- If the boundary between old and new coatings contains high spots or depressions, remove the high spots by sanding with 180 grit or finer abrasive.
- Remove sanding residue by wiping with a cheesecloth moistened with MEK and wipe the surface dry with a clean cheesecloth.
- Fill depressions with coating material, using the cotton swab and straight-edge leveling method described for minor repairs.
- Allow basecoat material to become tack free before applying topcoat.
- If required, perform spray application of topcoat (just enough to cover basecoat).
- Cure per manufacturer's instructions.

4.2 FILMS

4.2.1 Laboratory Test Results

Film evaluations under the previous study (ref. 1) showed that the bond strength of the promising film materials (Tradlon, Kapton, Kynar, and UHMW Polyolefin) to 2024-T3 clad aluminum was relatively low after 24-hour exposure to water, humidity, jet fuel, or hydraulic fluid. Improved bond strength was required to warrant further consideration of film applications to low-erosion wing-surface areas. A target peel strength of 8.7 kg/cm (10 lb/in) of width had been established, and none of the films achieved this bond strength.

Under this program, additional adhesive screening was performed on a limited basis due to the priority assigned to liquid coatings. The adhesive search attempted to select materials that could be readily applied over large areas. Selection

considerations included room-temperature curing characteristics, peel strength, leveling characteristics (viscosity), pot life, and hardness. The adhesives tested included the following:

Urethanes

23-700	Essex Chemical
1900	Cal Polymers
UR2139	H. B. Fuller
UE25	Isochem

Polysulfides

FE 1402	H. B. Fuller
Pro Seal 899	Essex Chemical
2133	Tra-Con

Modified Epoxy

A-1186-B	B. F. Goodrich

Test Specimen Preparation—The film candidates were bonded to 2024-T3 alclad aluminum. Surface preparation consisted of Scotchbrite abrasion; an Alkanox clean; an Alodine 1200 application; and a BMS10-79, Type II primer application. Adhesives and films were applied and smoothed with a Teflon blade to remove excess resin and air. Prior to bonding , the films were Freon TF solvent cleaned. The specimens were vacuum bagged and allowed to cure for varying periods from 3 to 14 days at room temperature and were post-cured at 65.6°C (150°F) for 6 hours to ensure full cure prior to testing. No restraint or vacuum pressure was used during post-cure. Each of the adhesives were applied to Tradlon, Kapton, and Kynar films. UHMW polyolefin contains a pressure sensitive adhesive.

Screening Test Results—The screening tests consisted of peel strength measurements performed on the four bonded film candidates, without environmental exposure and after 24-hour immersion in water and Skydrol. Peel tests were performed in accordance with ASTM D903.

The peel strength results, which are listed in Table A-9 of Appendix A, show that only moderate success was achieved in bonding films with the adhesives evaluated. Where peel strength values are not provided in the table, the tests were not performed due to poor film adhesion. After post-cure these specimens either blistered or the film became unbonded.

The polysulfide adhesives were the only materials to provide any measure of bond strength. Fuller FE 1402 exhibited moderate bond strength with the three films, both before and after environmental exposure. Essex No. 899 exhibited moderate bond strength with Tradlon and Kapton and no bond strength with Kynar. Tra-Con No. 2133 demonstrated excellent bond strength with Kapton and low bond strength with Tradlon. The UHMW polyolefin also demonstrated moderate bond strength before and after environmental exposure. The peel strengths were below the target value of 8.7 kg/cm (10 lb/in) except for Tra-Con 2133 with Kynar film. Tra-Con 2133, however, appeared somewhat hard and brittle after curing. Since the failure mode in most tests was between the film and adhesive, it is recommended that film etching be investigated in any future adhesion studies.

4.2.2 Application Process

Application of films to wing surface areas is expected to involve an extension of the application developed in the laboratory. The surface would be prepared by cleaning and priming as previously described. Adhesive would be brushed, rolled, or sprayed on to a specified thickness or applied as a film. The plastic film would be applied similar to wallpaper application. With tension applied to the ends of the sheet, the film would be smoothed with a squeegie and rolled to remove air and excess adhesive. A vacuum pressure diaphragm would be applied over the film to maintain uniform pressure while curing. Fastener penetrations in the wing surface would require sealing prior to adhesive application. This procedure would entail detailed studies of the wing geometry and application methods prior to undertaking feasibility demonstrations.

4.2.3 Repair and Maintenance

Film damage probably would occur in one of two forms, scuffing of the surface or debonding of the film from the substrate followed by tearing or peeling. It is possible that localized scuffing due to foreign-object damage could be repaired by applying a coating of adhesive over the damaged areas, followed by careful smoothing prior to curing. In case of torn or peeled film, the probable repair procedure would involve removal of adjacent areas of film back to where the film/substrate bond is unaffected and inlaying a patch of film of the exact size and shape. Much care would be required to ensure that the film butt joints were faired and sealed to prevent recurrence of failure. A well defined repair procedure must be preceded by large-scale film application research.

4.3 FLIGHT SERVICE EVALUATIONS

As reported in Reference 1, a flight service evaluation of CAAPCO B-274 and Chemglaze M313 was begun in September 1978. Coatings were applied to wing leading-edge slats and to the horizontal tail leading edge of a Continental Airlines (CA) 727 in Air Micronesia service. The evaluation was concluded in November 1979. Similar evaluations were begun in November and December 1979 on Delta Air Lines and CA 727s, respectively, to be flown on U.S. domestic routes. The three evaluations are discussed in the following paragraphs.

4.3.1 Continental Airlines (Air Micronesia)

Coatings were applied to the leading edges of wing leading-edge slats and the horizontal tail of a CA 727 flying Pacific island routes (Air Micronesia). As shown in Figure 7, CAAPCO B-274 was applied to the left-hand surfaces and Chemglaze M313 to the right-hand surfaces. The airplane with the coatings logged 3082 flight hours and 2421 landings during the 14-month evaluation period.

The airplane operated in a severe rain erosion environment, and some operations were off coral runways. Table 3 indicates the high level of rainfall in the Air Micronesia route system—about three times the level experienced in U.S. domestic operations (ref. 5). Furthermore, the ratio of flight hours to landings yields an average flight duration of 1.27 hours, indicating that much of the total flight time was at low altitudes where most rainfall occurs. The effects of coral dust (fig. 8) are unknown, but certainly contribute to surface erosion.

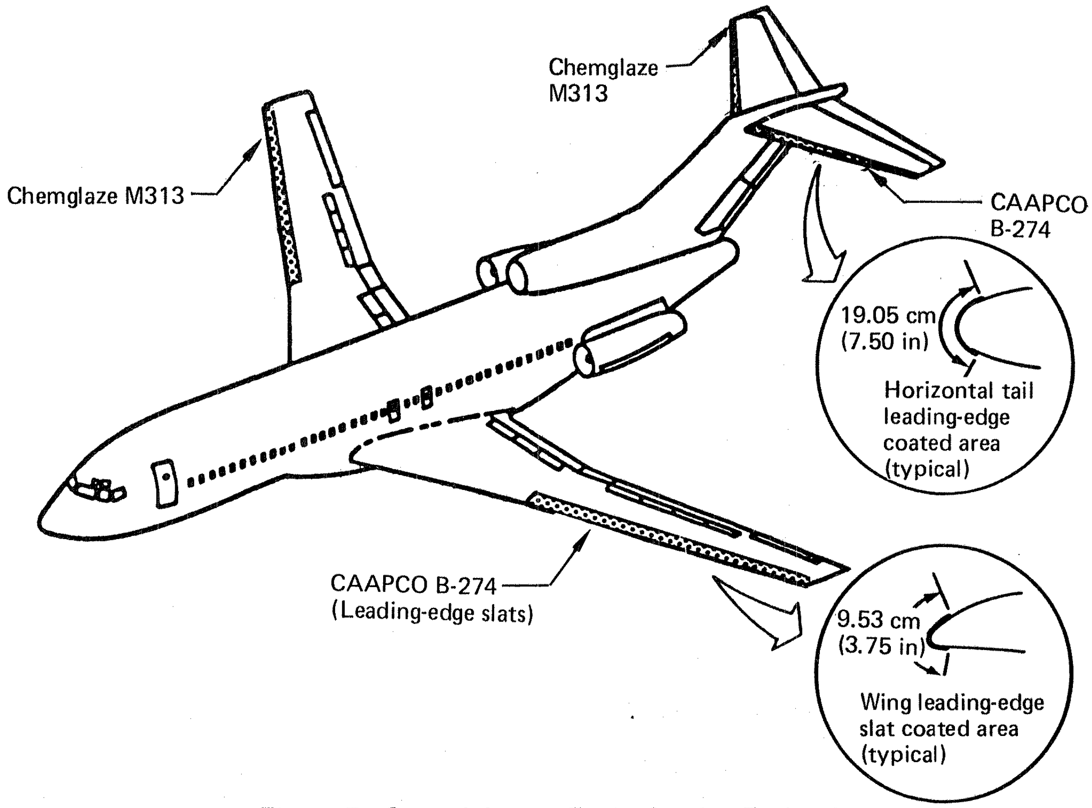


Figure 7. Coated Areas—Flight Service Evaluation

Table 3. Air Micronesia Route System

Area	Annual rainfall,	
	cm	(in)
Guam/Rota	217.2	(85.5)
Honolulu	58.7	(23.1)
Kwajalein	260.6	(102.6)
Majuro	144.8	(57.0)
Okinawa	210.3	(82.8)
Palau	389.9	(153.5)
Ponape	260.6	(102.6)
Saipan/Tinian	217.2	(85.5)
Taiwan	192.8	(75.9)
Tokyo	156.5	(61.6)
Truk	376.7	(148.3)
Yap	260.6	(102.6)
Average annual rainfall, 15 U.S. cities: 88.7 cm (34.93 in)		

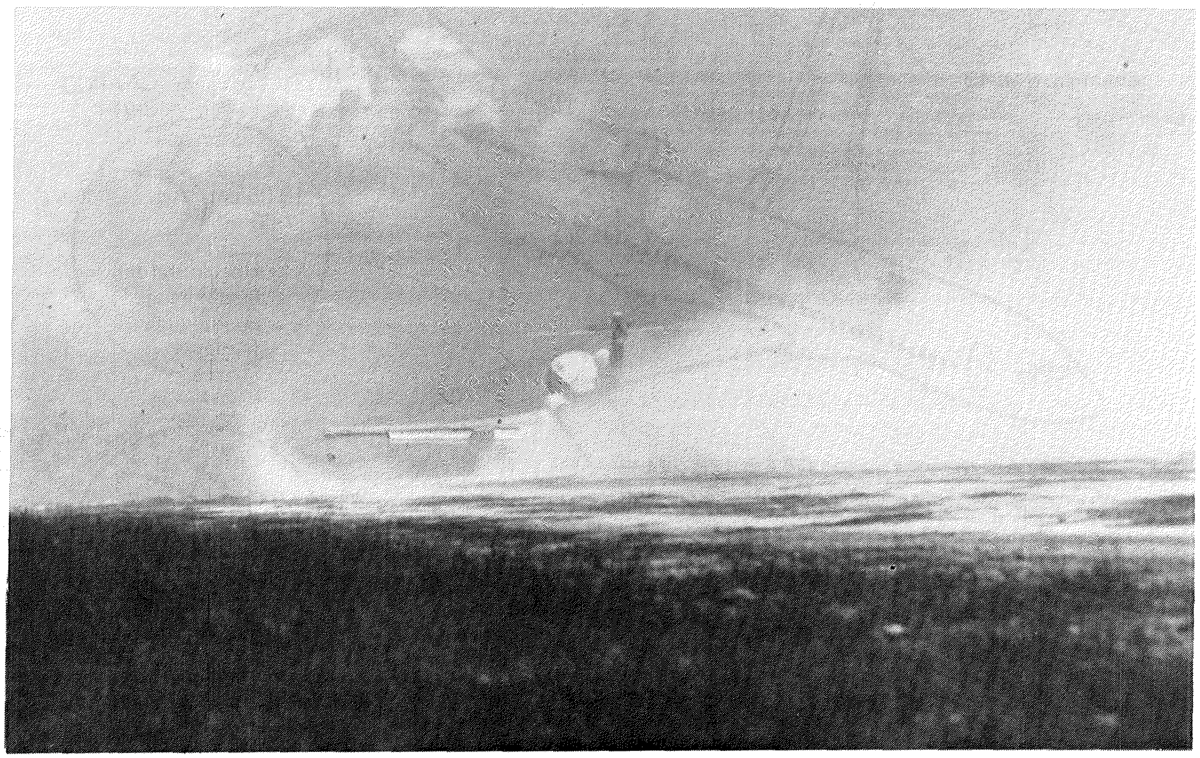


Figure 8. Landing on Coral Runway—Truk

Periodic inspections were made throughout the evaluation period by airline maintenance personnel at Guam. These reports were sent to the Contractor, who also inspected the coatings at the conclusion of the evaluation. A discussion of coating application procedure, the field reports, and an evaluation of the coatings follows.

4.3.1.1 Coating Application Procedures

Coatings were applied during September 1978 by CA in their maintenance hangar at Los Angeles International Airport. Application procedures included cleaning the surface to be coated, priming, and applying the coatings. General procedures provided by the coating manufacturers were supplemented with instructions provided by the Contractor. As shown in Figure 9, CAAPCO was applied to slats 1 through 4 and horizontal tail leading-edge sections 9 through 11. Chemglaze was applied to slats 5 through 8 and horizontal tail sections 12 through 14. All parts, except slats 2 and 7, were coated while installed on the airplane, following the procedures listed below. Slats 2 and 7 were removed for repair and were coated, subsequent to the other parts, using modified procedures.

1. Mask area to be coated.
2. Clean area using Scotchbrite and alkaline cleaner.
3. Alodine the cleaned surface.
4. Apply epoxy primer [0.013 to 0.025 mm (0.5 to 1.0 mils)] to area to be coated.
5. Allow primer to dry 30 to 60 minutes.
6. Apply coating [recommended temperature 21.1°C (70°F) or greater]:

CAAPCO B-274

a. Mix with activator (pot life 4 hours).
b. Apply 9 to 12 coats at 10 to 30 minute intervals to achieve 0.254 to 0.356 mm (10 to 14 mils) coating thickness.
c. Cure 2 to 3 days (cure can be accelerated by heat).

Chemglaze M313

a. Mix with activator (pot life 2 hours).
b. Apply 3 to 5 coats at 1 to 2 hour intervals to achieve 0.254 to 0.305 mm (10 to 12) mils coating thickness.
c. Cure 3 to 5 days (cure can be accelerated by heat).

After curing for approximately 24 hours, an attempt was made to remove the masking tape. This resulted in edge lifting of the CAAPCO coating. The coatings were allowed to cure an additional 3 days and the remaining tape was removed using a knife at the edge of the tape where necessary.

The edge lifting indicated a poor bond near the edges of the coated area, therefore, the surface preparation procedure was modified for slats 2 and 7. On these slats, the area cleaned and alodined extended about 10 mm (0.4 in) beyond the edges of the area to be coated. After alodining, a second masking tape was applied to expose only the area to be coated. This ensured that the entire area was properly prepared. A good edge bond resulted, and the masking tape was removed without difficulty.

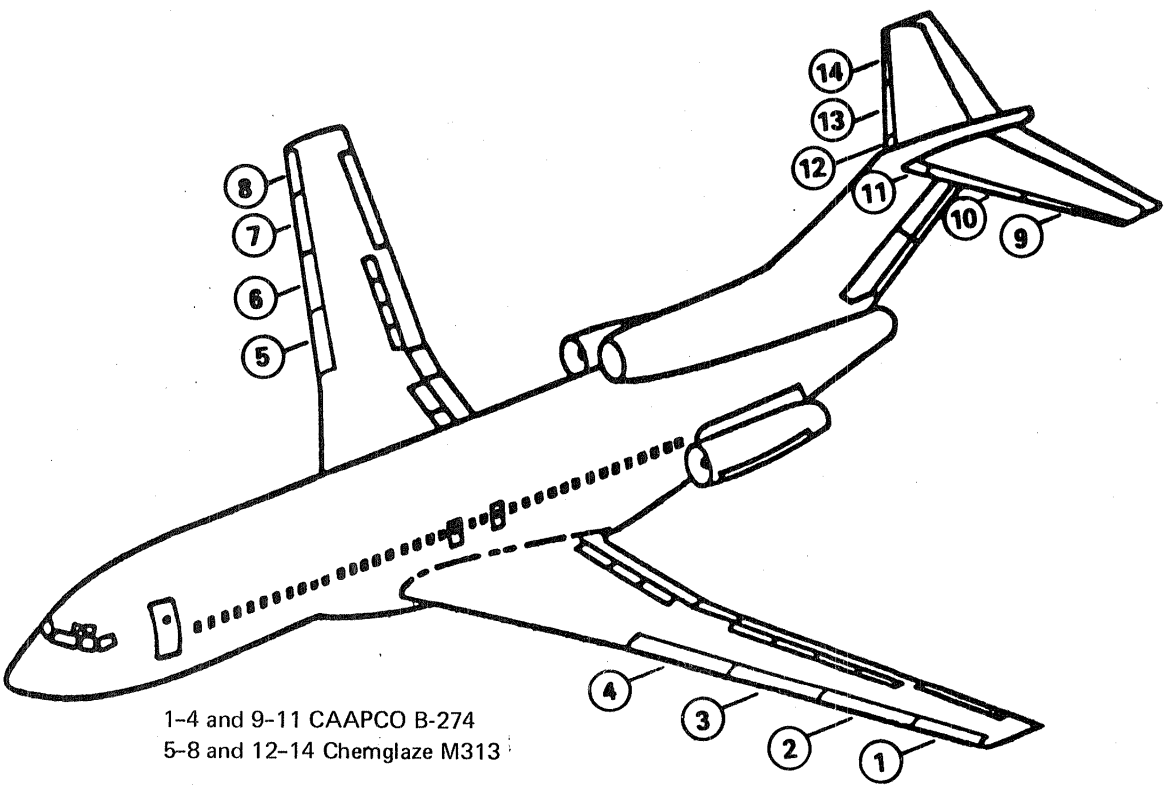


Figure 9. Coating Configuration on Continental Airlines 727

Different epoxy primers were used on the inboard and outboard halves of slat 2. At the end of the service evaluation, the coating was missing from the outboard half of that slat. This is discussed under Field Reports.

4.3.1.2 Field Reports

The coated airplane returned to commercial service on 15 September 1978, flying the route system shown in Figure 10. During the 14-month service evaluation that followed, CA maintenance personnel at Guam periodically inspected the coatings and filled out a report sheet that was sent to CA-Los Angeles, and from there to the Contractor. Some of the reports were supplemented with Polaroid color photos taken on the Guam flight line. Although the coatings were inspected periodically, they did not receive maintenance or repair during the entire flight service evaluation.

On the airplane's ferry flight from Los Angeles to Guam, Contractor personnel made a visual inspection at Honolulu and reported, " . . . on both left wing and horizontal stabilizer, found coating actually peeling away around periphery both upper/lower edges. It appeared as though poor bond was the cause". This condition, noted in the previous section as a masking tape removal problem with the CAAPCO coating, also was reported in subsequent field reports throughout the evaluation.

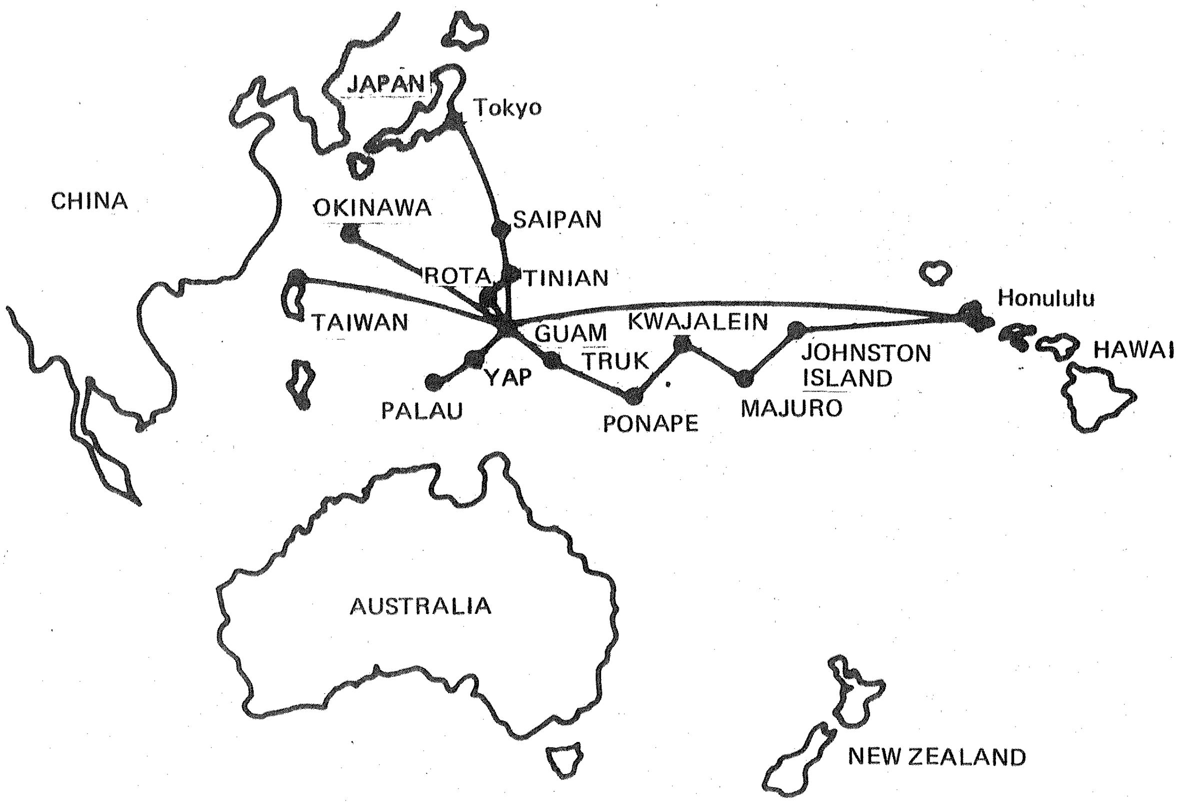


Figure 10. Air Micronesia Routes

Tables 4 and 5 summarize the field reports as flight hours and landings (number of flights) were accumulated. Photos contained in Figures 11 through 14 illustrate the deterioration of various coated areas with time, and are keyed to specific remarks in the tables. In some cases it was not clear from the field reports if deterioration resulted from foreign object damage, peeling, or erosion, therefore, some interpretation of report terms was exercised in the preparation of Tables 4 and 5, based on examination of the photographs.

General observations from the field reports are:

- Most of the CAAPCO deterioration occurred after about 2000 flight hours.
- Slats 5, 6, and 8 (coated with Chemglaze) showed early deterioration that increased at only a moderate rate through the remainder of the evaluation.
- Slat 7 (coated with Chemglaze) was in good condition at the end of the evaluation, with no edge peeling or leading-edge erosion.
- Horizontal tail leading edges showed less erosion of coatings than slat leading edges.
- The inboard end of coated parts on swept surfaces is especially susceptible to local erosion.
- Leading-edge erosion tends to increase as leading-edge radii become smaller.

4.3.1.3 Evaluation Results

The flight service evaluation was concluded with return of the airplane to the CA maintenance base in Los Angeles on 22 November 1979 (fig. 14). The coatings had accumulated 3082 flight hours and 2421 landings. Contractor personnel inspected the airplane and made a photographic record of the condition of the coatings. A discussion of the findings follows on a per-item basis.

Slat 1 (CAAPCO)—Figure 15a shows erosion along the leading edge and on the lower surface. The edge peeling, reported after application of the coating, had progressed toward the leading edge, and in two areas included the leading edge. Just outboard of the slat midspan, the leading edge had been impacted by an object that left a dent (fig. 15b). Coating was missing from the impacted area.

An "alligator skin" appearance, that was common to most of the CAAPCO-coated parts, is visible in Figure 15b. This condition typically is caused by ultraviolet (UV) exposure and could be corrected by adding black pigment to the coatings, or by applying a UV protective topcoat.

Slat 2 (CAAPCO)—The coating was gone from the outboard half of the slat (fig. 16a.) This condition started at the outboard end after about 2000 flight hours and progressed inboard. Coating on the inboard half remained in good condition (fig. 16b), showing no edge peeling or erosion.

A close inspection of exposed primer on the outboard portion of the slat indicated that BMS 10-11 had been used on that area. A later review of the CA coating application record revealed that different epoxy primers had been used on the

Table 4. Field Report Summary—CAAPCO B-274

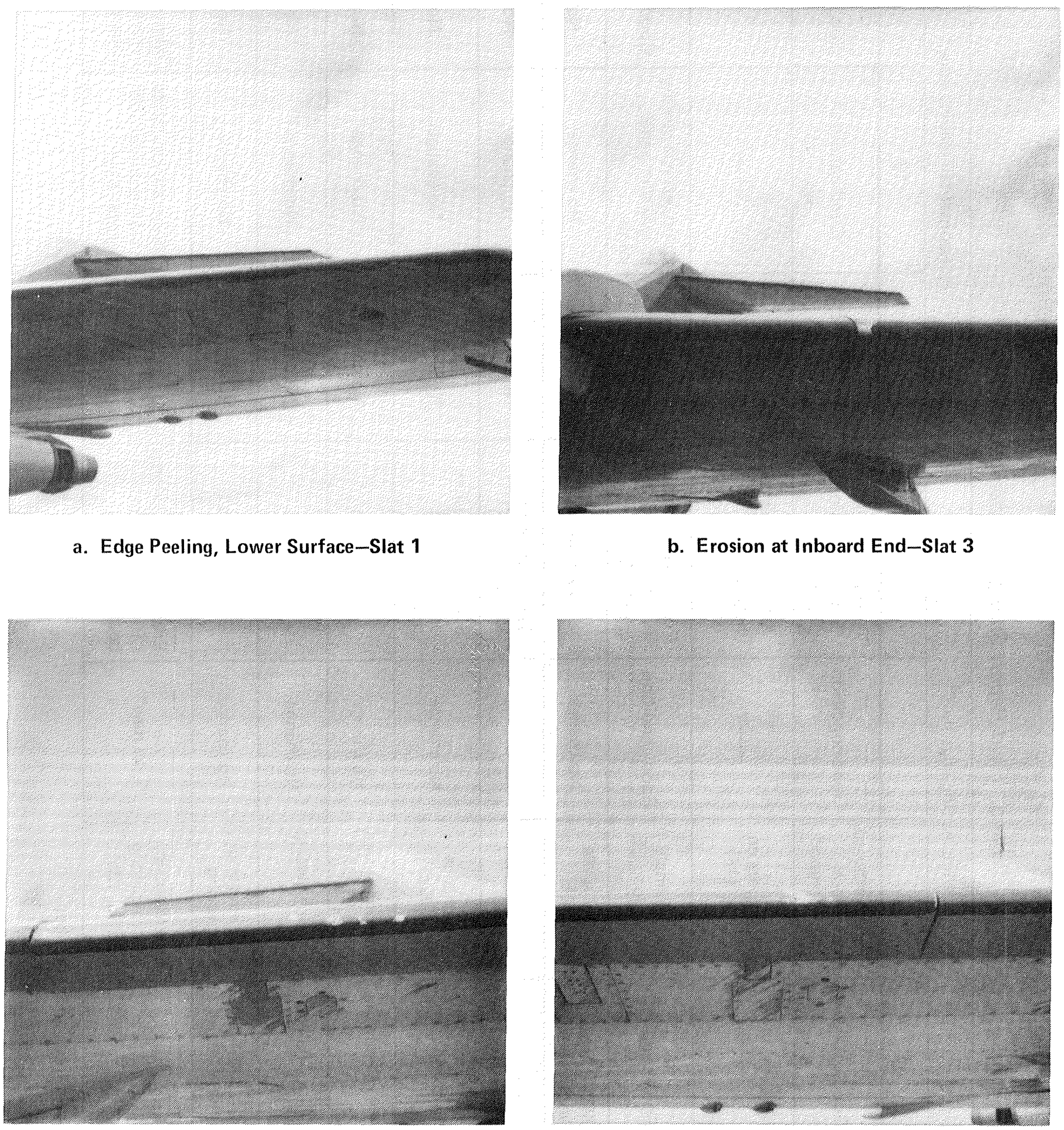
Flight hours	Landings	Wing leading-edge slats[a]				Horizontal tail leading edge[a]		
		1	2	3	4	9	10	11
347	249	LE good, edge peeling lower surface	Good condition	Erosion inboard end, general condition good	Erosion inboard end, edge peeling lower surface	LE good, edge peeling lower surface	Edge peeling inboard end on lower surface	Good condition
Approx. 500	Approx. 400	No change, edge peeling lower surface (fig. 11a)	—	No change, erosion inboard end (fig. 11a)	—	—	—	—
1079	807	No change	Good condition	Three small spots, LE erosion	Good condition	No change	No change	No change
Approx. 1300	Approx. 1000	Edge peeling lower surface	No change	No change	No change	No change	No change	Small spot on LE
1521	1188	No change	No change	No change	No change	No change	No change	No change
1721	1356	Edge peeling lower surface (fig. 12a)	No change	No change (fig. 12b)	No change	No change	No change	No change, small spot on LE
1916	1505	No change	No change	No change	No change	LE spotting	LE spotting	LE spotting
2183	1718	No change	Piece approx. 5 cm (2 in) wide peeled off LE	No change	No change	LE spotting	LE spotting	5 cm (2 in) piece peeled off inboard end
2395	1896	No change	Large area missing, outboard end	No change	Erosion outboard end	No change	No change	No change
2591	2047	Minor erosion upper and lower edges	Impact damage 2 spots. 41 cm (16 in) missing, outboard end (fig. 13a)	Minor erosion upper and lower edge, also inboard end	Erosion inboard end, approx. 5 cm (2 in)	Moderate pitting and erosion, outboard end	LE spotting (fig. 13a)	Minor LE spotting

[a]Refer to Figure 9 for part location by number

Table 5. Field Report Summary—Chemglaze M313

Flight hours	Landings	Wing leading-edge slats[a]				Horizontal tail leading edge[a]		
		5	6	7	8	12	13	14
347	249	Good condition	Erosion inboard end, general condition good	Good condition	Small blister on LE, erosion inboard end	Good condition	Good condition	Good condition
Approx. 500	Approx. 400	—	Small spots on LE (fig. 11c)	—	Small peeled area near inboard end on LE (fig. 11d)	—	—	—
1079	807	Good condition	Several small spots along LE	Good condition	Peeled area approximately 2.5 x 15.2 cm (1 x 6 in)	Good condition	Good, except peeling at two skin panel joints	Good condition
Approx. 1300	Approx. 1000	Minor erosion spotting at LE	Several spots along LE	No change	No change	No change	No change	No change
1521	1188	No change	No change	No change	Several areas of LE erosion	No change	No change	No change
1721	1356	Minor erosion spotting along LE	No change (fig. 12c)	No change	Significant erosion one area of LE (fig. 12d)	No change	No change	No change
1916	1505	Minor spotting on LE	Spotting along entire LE	No change	No change	No change	No change	No change
2183	1718	Minor flaking (?)	Spotting getting worse	No change	No change	No change	No change	No change
2395	1896	LE spotting increasing	LE spotting increasing	No change	No change	No change	No change	No change
2591	2047	Many minor spots on LE	Severe erosion spotting along LE (fig. 13c)	"Like new"	Erosion spotting along LE most severe inboard end	Very minor erosion spotting	Erosion at skin joints, plus other minor spotting (fig. 13d)	Minor spotting erosion at outboard end

[a]Refer to Figure 9 for part location by number



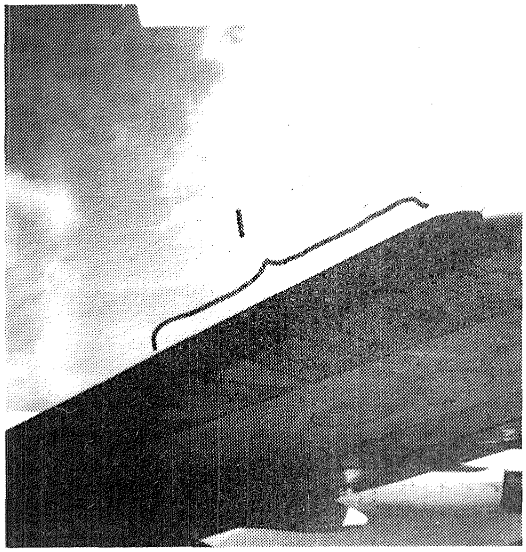
a. Edge Peeling, Lower Surface—Slat 1

b. Erosion at Inboard End—Slat 3

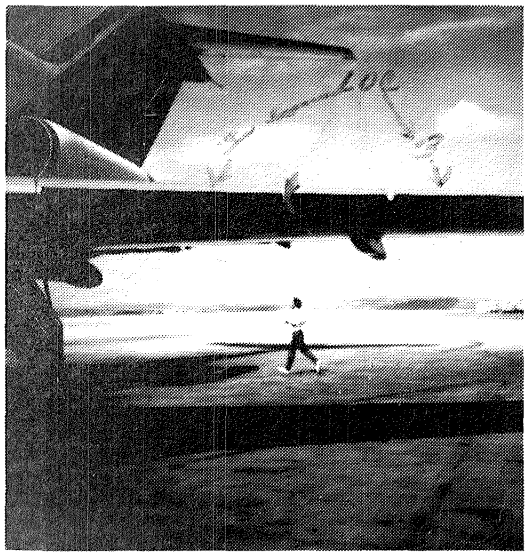
c. Leading-Edge Erosion Spots—Slat 6

d. Erosion at Inboard End—Slat 8

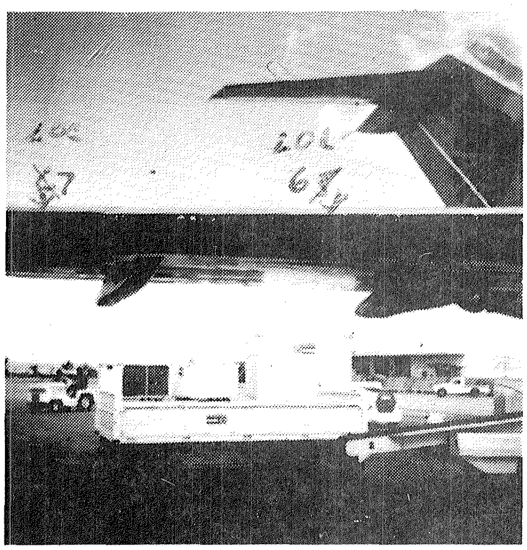
Figure 11. Coating Condition at 500 Flight Hours



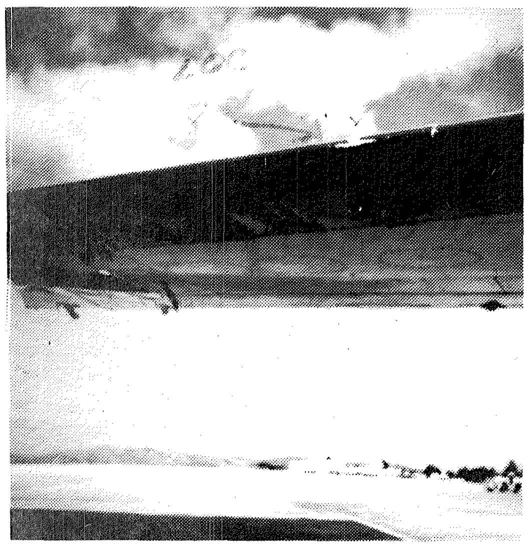
a. Lower Surface Edge Peeling—Slat 1



b. Erosion at Inboard Edge—Slat 3

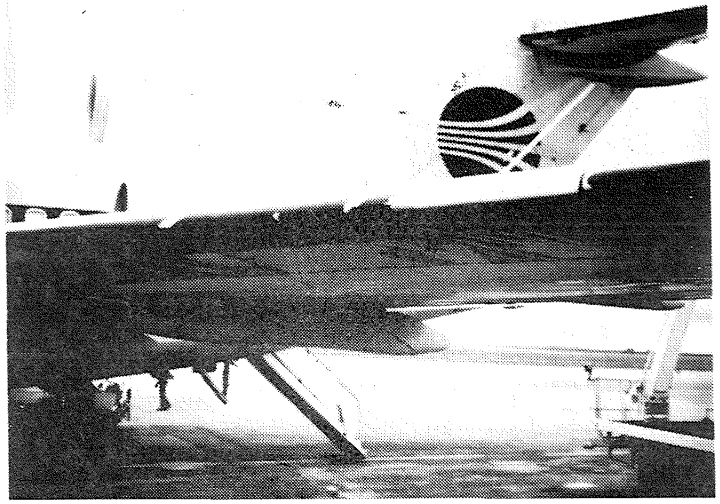


c. Leading-Edge Erosion—Slat 6

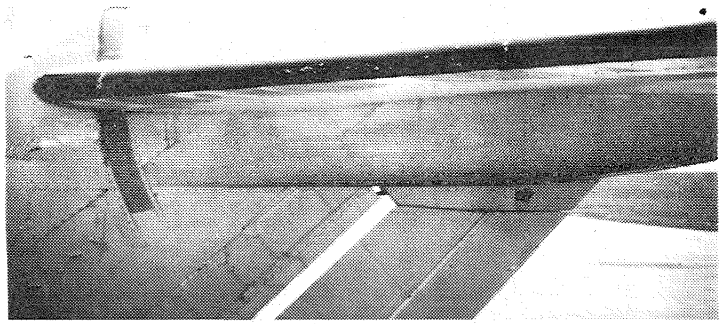


d. Erosion Near Inboard End—Slat 8

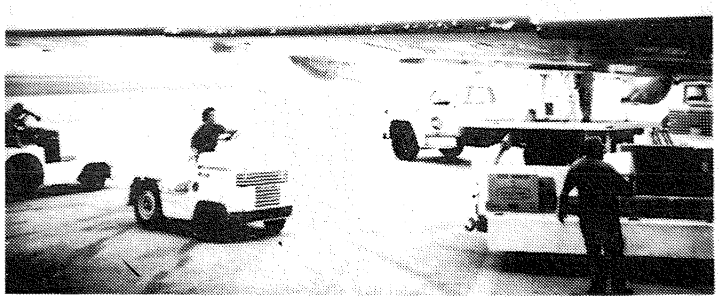
Figure 12. Coating Condition at 1,721 Flight Hours



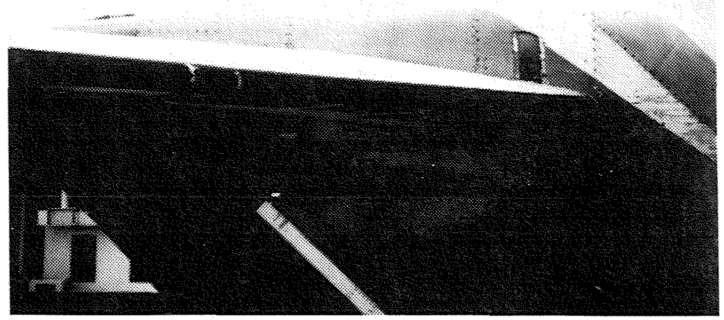
a. Coating Eroded From Outboard 41 cm (16 in) of Slat 2



b. Coating Erosion on Left Horizontal Tail Leading Edge



c. Severe Leading-Edge Erosion—Slat 6



d. Erosion at Skin Panel Joints, Right Horizontal Tail Leading Edge

Figure 13. Coating Condition at 2,591 Flight Hours

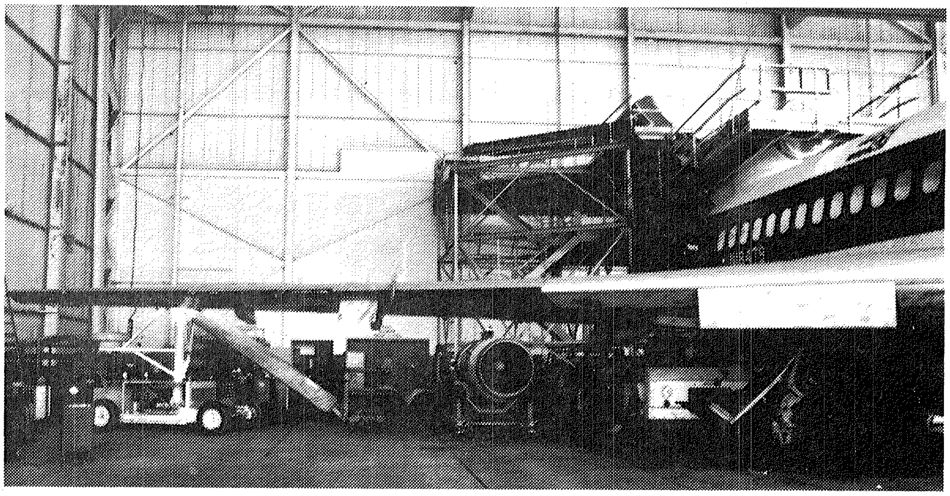
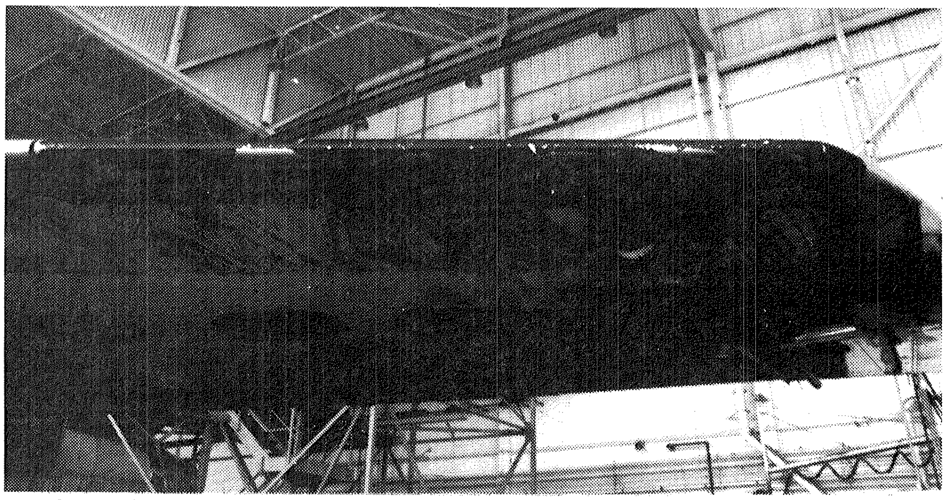
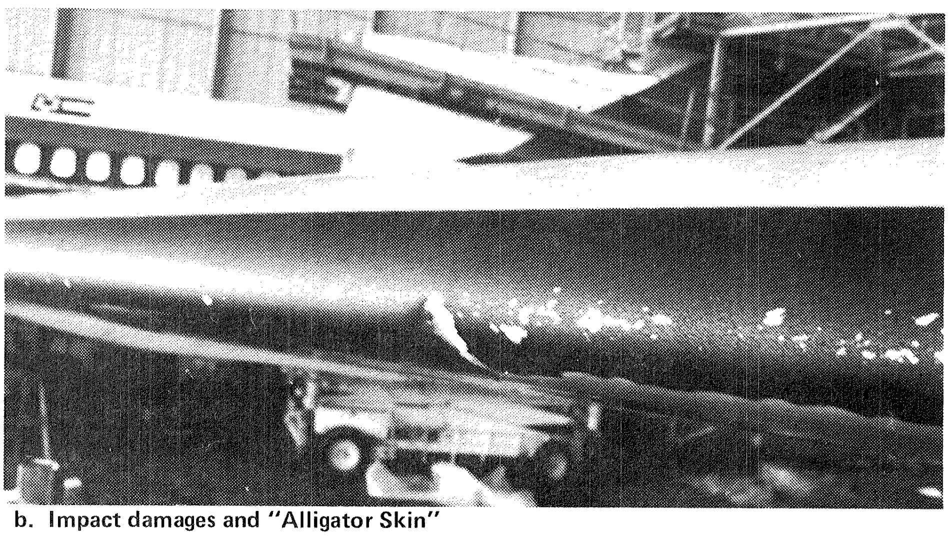


Figure 14. Airplane in Maintenance Hangar—Los Angeles

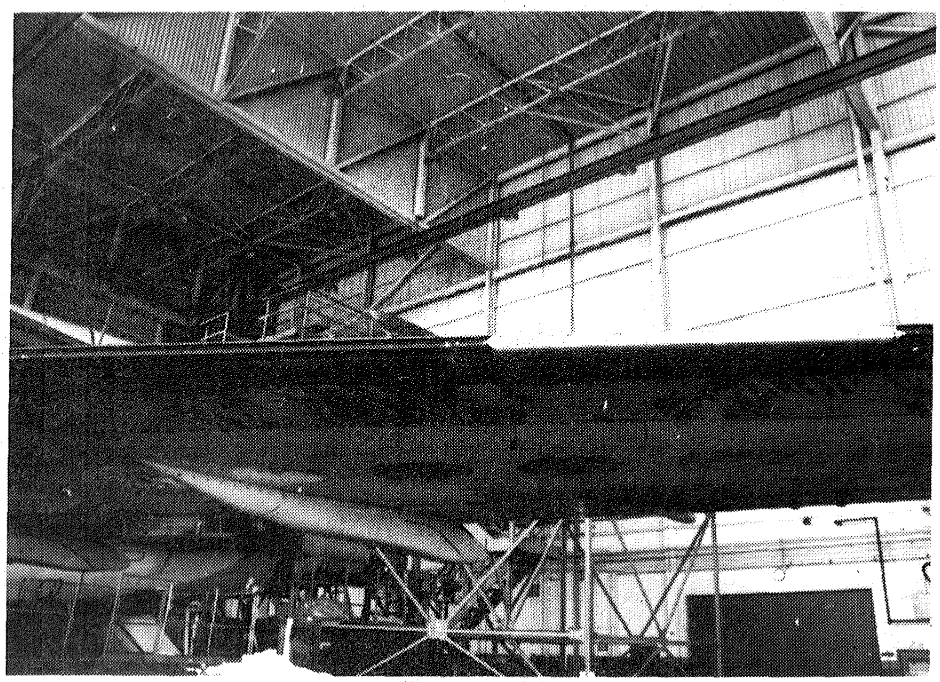


a. Lower-Surface Erosion Progressed to Leading Edge—Two Areas

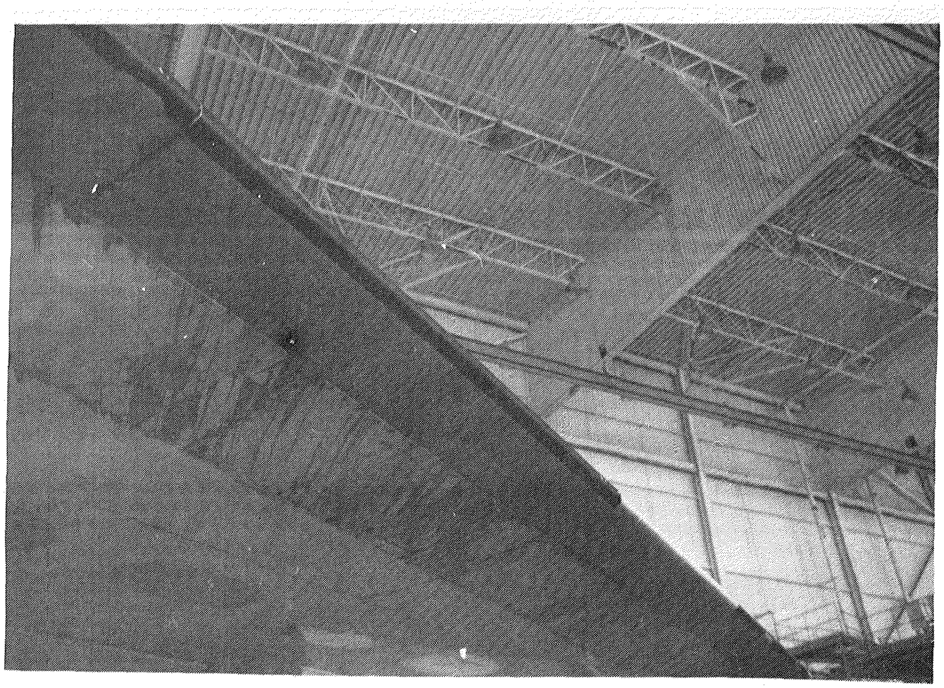


b. Impact damages and "Alligator Skin"

Figure 15. Slat 1



a. Coating Gone on Outboard Half



b. No Edge Peeling

Figure 16. Slat 2

inboard and outboard halves of the slat showing that BMS 10-79 was applied to the outer half and BMS 10-11 was applied to the inboard half. It was suspected that the reverse was true because BMS 10-11 has the lower cohesive strength.

Slat 3 (CAAPCO)—Most of the coating was intact (fig. 17), with the exception of a few small erosion spots on the leading edge and erosion at the inboard end that extended about 7.6 cm (3 in). The inboard end of several slats showed coating erosion. This was probably due to exposure of the coating edge to the spanwise crossflow component of the airstream that occurs at the leading edge of swept surfaces.

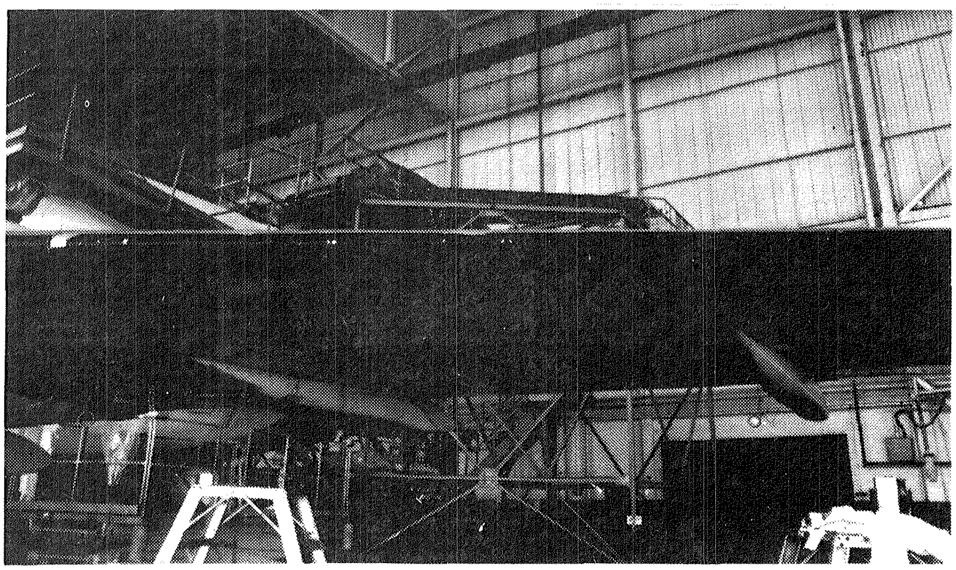


Figure 17. Slat 3 Erosion at Inboard End and Minor Spotting

Slat 4 (CAAPCO)—This slat was in good condition (fig. 18), except for two or three minor erosion spots on the leading edge and erosion of the coating at the inboard end.

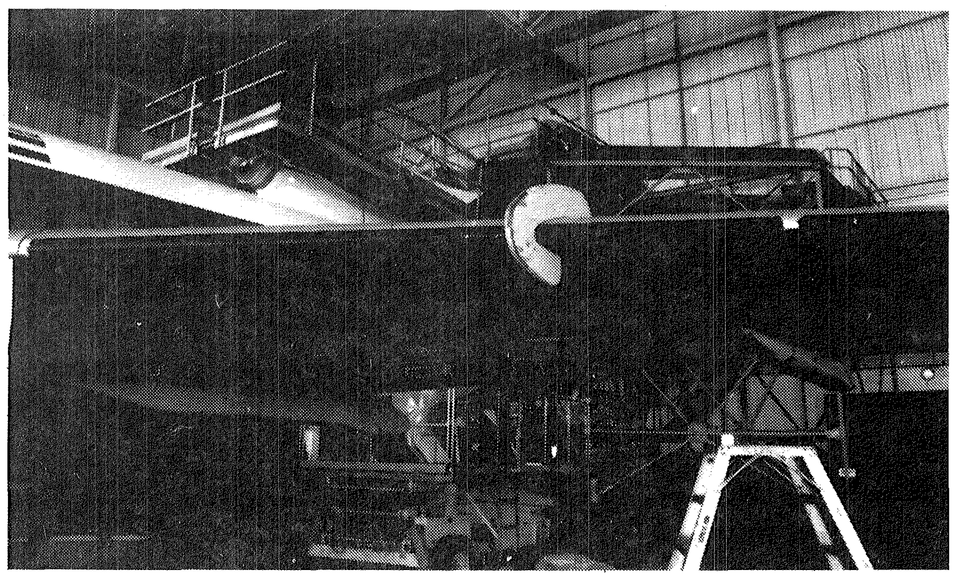


Figure 18. Slat 4 Erosion at Inboard End

Slat 5 (Chemglaze)—Several small erosion spots occurred along the leading edge, most of which were inboard of the flow fence (fig. 19). Many of the spots were at fastener heads and were less than 2.54 cm (1 in) in diameter. The upper-surface edge of the coating showed no evidence of peeling or erosion. The lower-surface edge also showed no deterioration, as was typical of all the Chemglaze-coated slats.

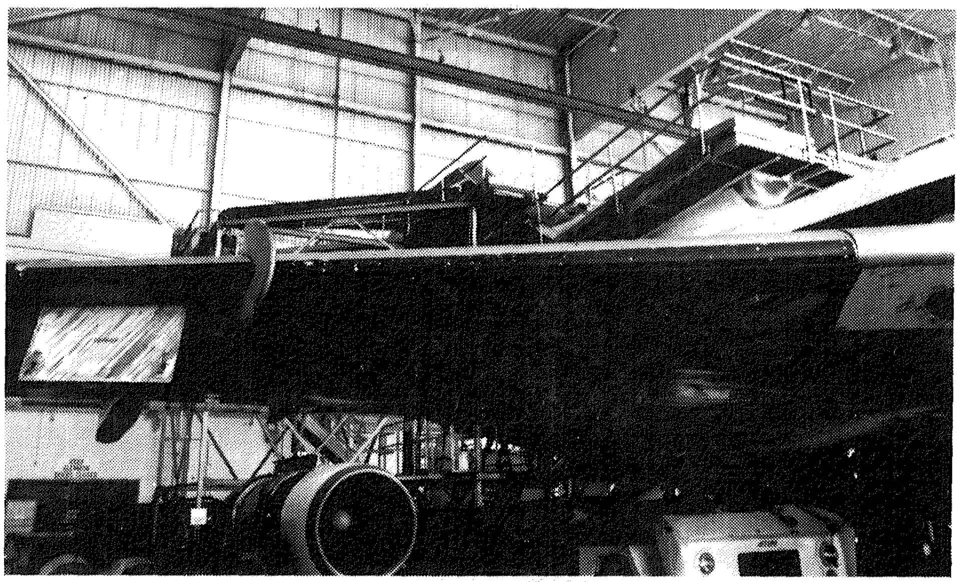


Figure 19. Slat 5 Erosion Spotting Along Leading Edge

Slat 6 (Chemglaze)—This slat had the most severe erosion of the four Chemglaze-coated slats. Leading-edge erosion occurred all along the slat, predominantly at the inboard end (fig. 20). The upper-surface edge also had eroded forward in several areas along the span.

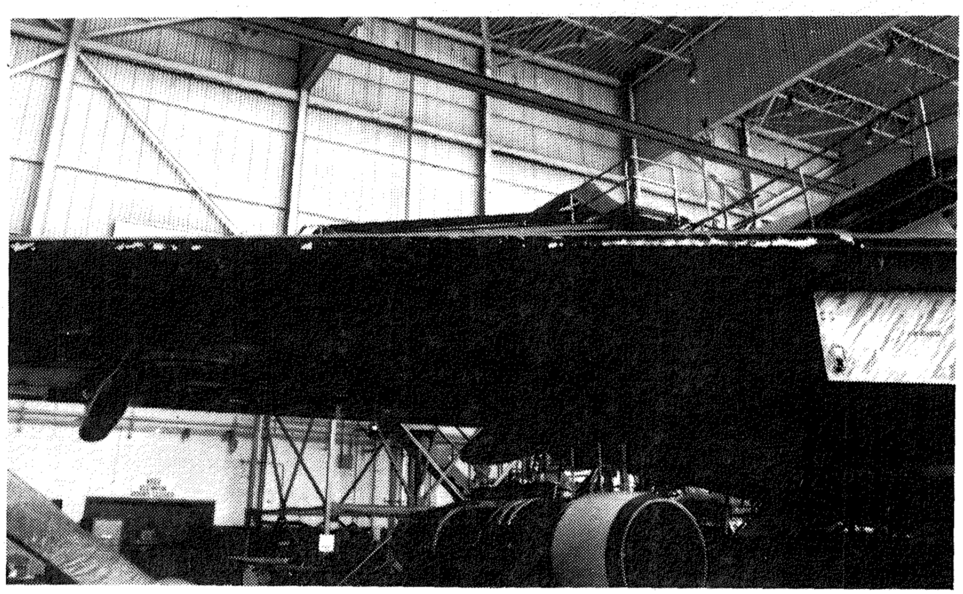
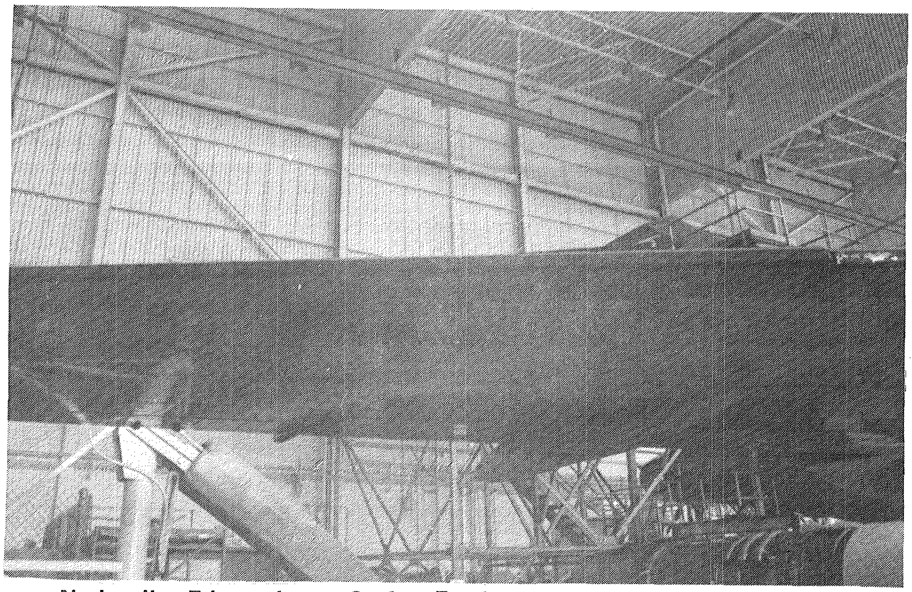
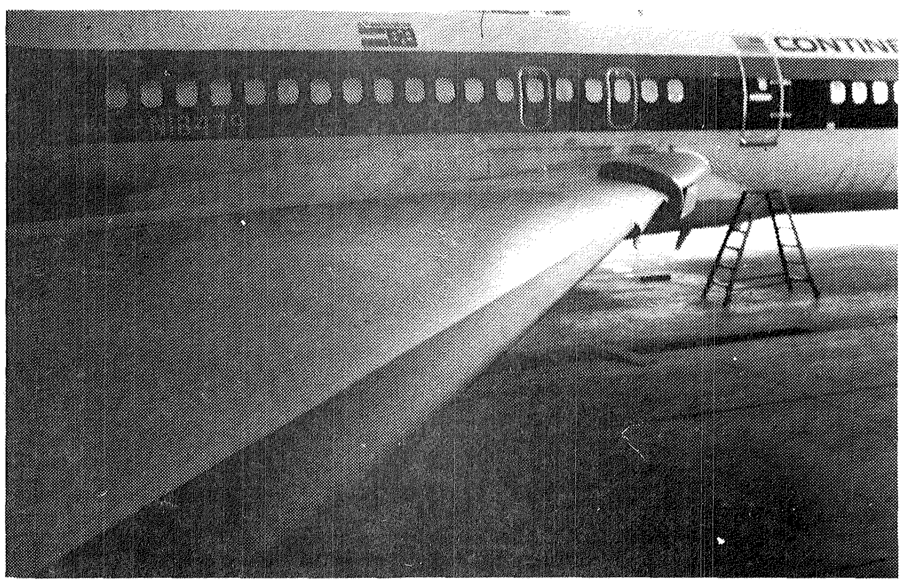


Figure 20. Slat 6 Severe Leading-Edge Erosion

Slat 7 (Chemglaze)—Figure 21 shows there was no evident deterioration of slat 7. Upper and lower edges of the coated area were uniform and straight. The leading edge had no erosion spots and, except for being slightly dull, was smooth and intact. This slat was in the best condition of any of the coated parts on the airplane. It is speculated that the modified application process used on slats 2 and 7 was preceded by careful cleaning and preparation of the surface for primer application. This rationalization is supported by the fact that the "best" slat was located between two adjacent slats (slats 6 and 8) that showed considerable deterioration.



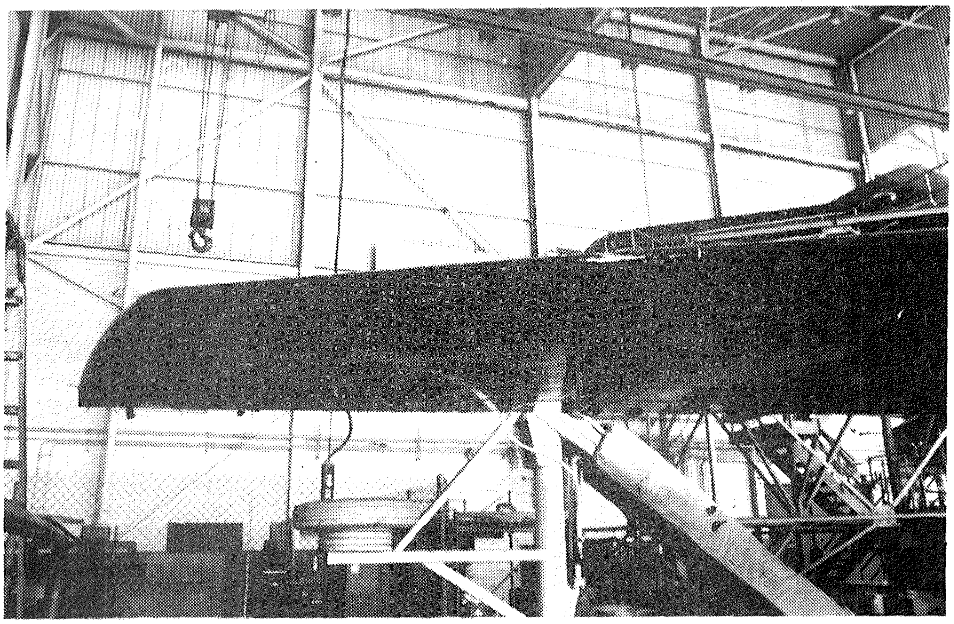
a. No Leading-Edge or Lower-Surface Erosion



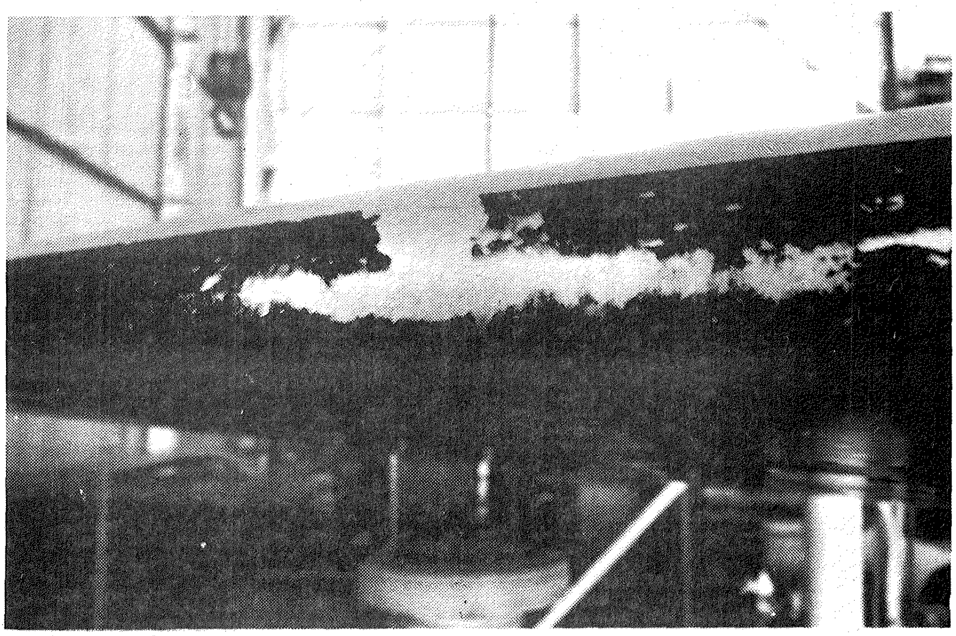
b. No Upper-Surface Edge Erosion

Figure 21. Slat 7

Slat 8 (Chemglaze)—The first field report of coating condition at 347 flight hours identified a small blister on the leading edge and erosion at the inboard end (fig. 22a). Later, the blister peeled and the exposed area increased in size through erosion. At the end of the flight evaluation about 40 cm (16 in) of leading edge was exposed, as shown in Figure 22b. Erosion at the inboard end of the slat did not increase with additional flight hours. At the end of the service evaluation it was only about 2.54 cm (1 in) wide.



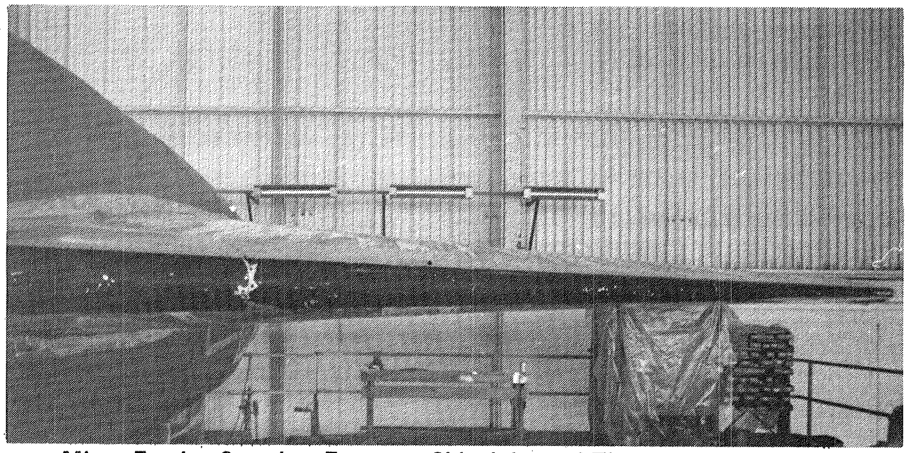
a. Severe Erosion, Inboard Leading Edge



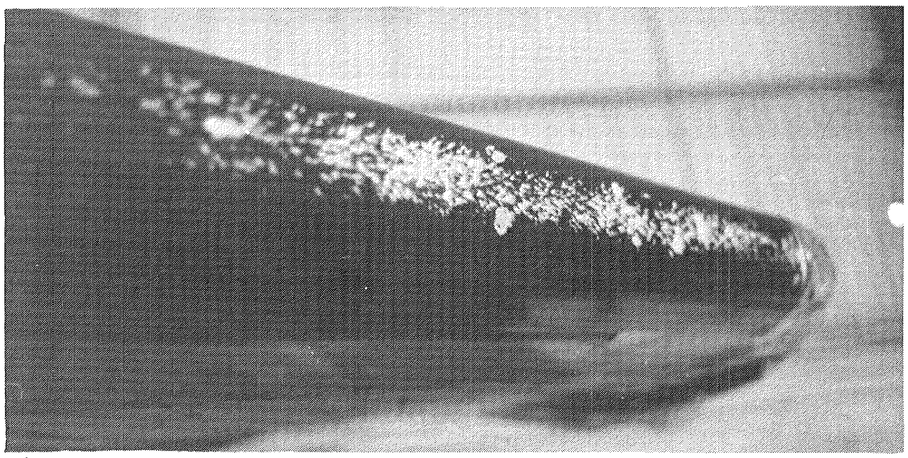
b. Closeup of Inboard Leading Edge

Figure 22. Slat 8

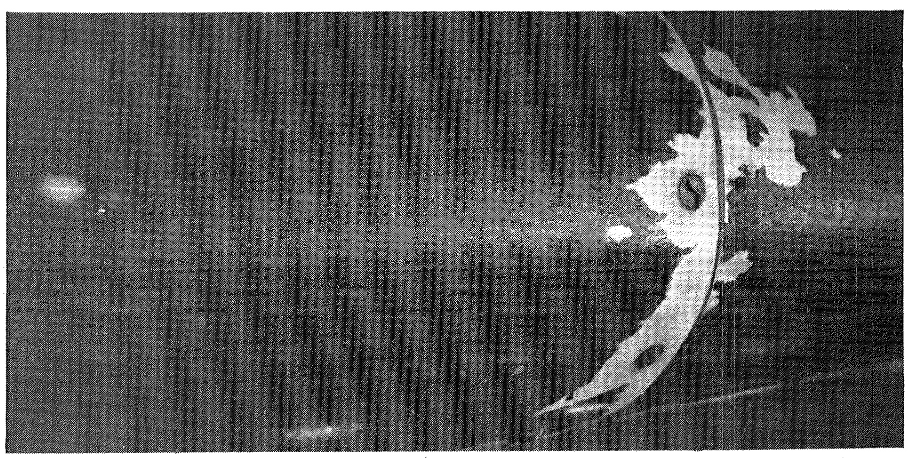
Left-Hand Horizontal Tail (CAAPCO)—Figure 23a shows the general condition of coatings on evaluation parts 9, 10, and 11. Part 9, extending from the tip to almost midspan, showed severe erosion at the outboard end (fig. 23b) over a length of about 61 cm (24 in). The remaining part 9 leading edge showed occasional leading-edge erosion spotting.



a. Minor Erosion Spotting, Except at Skin Joint and Tip



b. Severe Erosion at Tip



c. Peeling and Erosion at Skin Joint

Figure 23. LH Horizontal Tail Leading Edge

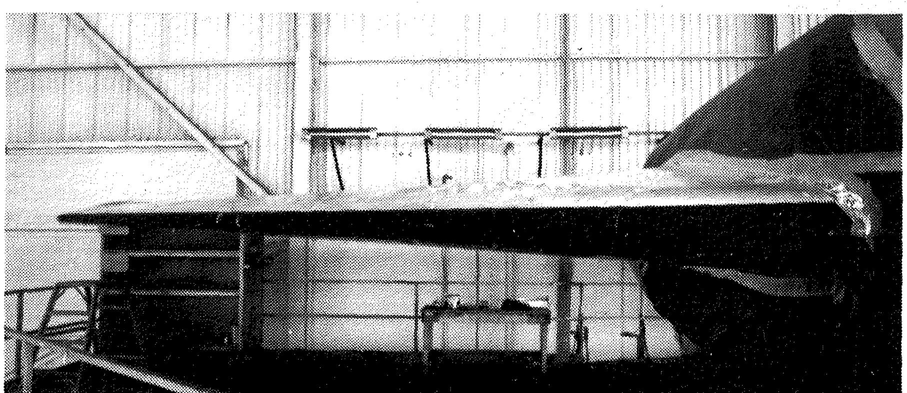
Part 10, extending inboard from semispan to near the centerline body, had several small erosion spots near both ends and a peeled/eroded strip at the skin joint of parts 10 and 11 (fig. 23c). Part 11, adjacent to the centerline body, had a few minor erosion spots and a few very small jagged spots that appeared to have been caused by impact from small, sharp objects.

The upper- and lower-surface edges showed some erosion that precipitated from edge lifting during removal of the masking tape. In general, the edge erosion progressed forward less than 2.54 cm (1 in), except at the lower-surface juncture of parts 10 and 11. At this location (fig. 23c) it extended into the peeled area at the juncture.

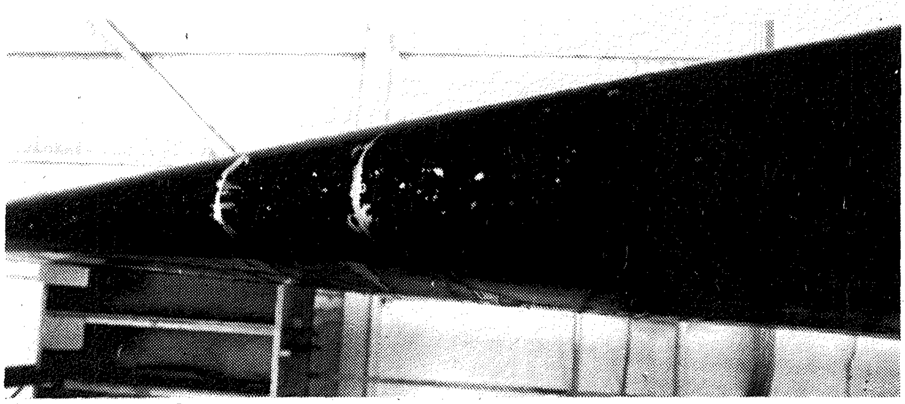
The entire coated surface of the left-hand horizontal tail showed, to a lesser degree, the "alligator skin" condition noticed on the left-hand wing slats.

Right-Hand Horizontal Tail (Chemglaze)—There was very minor erosion damage to the coating on the right-hand horizontal tail leading edge (fig. 24a). Minor erosion/peeling occurred at skin joints between parts 12 and 13, and between parts 13 and 14. Deterioration at the latter location is shown in Figure 24b by the double line of exposed skin on either side of a short, fixed leading-edge section separating parts 13 and 14. Figure 24b also shows small leading-edge erosion spots that were typical, but infrequent, along the entire leading edge.

Upper- and lower-surface edges of the coating were straight and uniform, showing no signs of erosion. The surface of the coating was in good condition.



a. Minor Isolated Spots—Fastener Heads and Skin Joints



b. Erosion at Midspan Skin Panel Joints

Figure 24. RH Horizontal Tail Leading Edge

4.3.1.4 Service Evaluation Summary

The Continental Airline's 727 in Air Micronesia service for 14 months provided a very severe service evaluation of surface coatings. The annual rainfall in the route system flown was nearly three times the average of 15 U.S. domestic air terminal cities, also, the airplane operated off coral runways part of the time.

No maintenance or repair of coatings was accomplished during the evaluation. The evaluation began with the Chemglaze-coated surfaces in good condition. Edges were well bonded to the surfaces and, with few exceptions, remained in good condition throughout the evaluation. Most of the edges of the CAAPCO-coated surfaces were lifted or peeled at the beginning of the evaluation. Edge erosion progressed at a moderate rate. Slat 2, which was coated with CAAPCO by a modified application procedure, did not have any edge erosion (inboard half, on which coating remained).

Leading-edge spotting of the Chemglaze began early in the evaluation but did not increase significantly until after about 2000 flight hours had accumulated. It is not known whether the early spotting was caused by a poor bond, foreign object damage, or erosion. Slat 7 survived the evaluation without any apparent damage, other than a slight dulling of the surface.

The surface of the Chemglaze coating did not appear to have deteriorated appreciably from UV exposure or other environmental factors. The surface of the CAAPCO coating showed some deterioration that has been described as "alligator skin" and also was slightly tacky.

The life of CAAPCO B-274 or Chemglaze M313 coatings as protection against surface erosion depends upon the care taken to properly prepare surfaces before coating. The surfaces must be thoroughly cleaned to provide a strong bond for the primer. Proper drying times after priming and during coating buildup should be observed. All work should be done in a dust-free, lint-free atmosphere to obtain a smooth, glossy coating surface.

A letter from CA to the Contractor, at the conclusion of the service evaluation, is included as Appendix B. The letter states, in part, "The service evaluation indicates the tested materials . . . will provide leading-edge protection without maintenance care for at least six months. After six months some maintenance will be required . . . to maintain the coatings in an aerodynamically smooth serviceable condition. Total recoating may be required between twelve and eighteen months on aircraft operating in a severe rain erosion environment."

The Air Micronesia evaluation provided much valuable experience in the application of surface coatings that could not be obtained in the laboratory. It clearly indicated the need for additional flight service evaluations to optimize and test procedures for the application of coatings in the real world of airline paint shops and maintenance hangers.

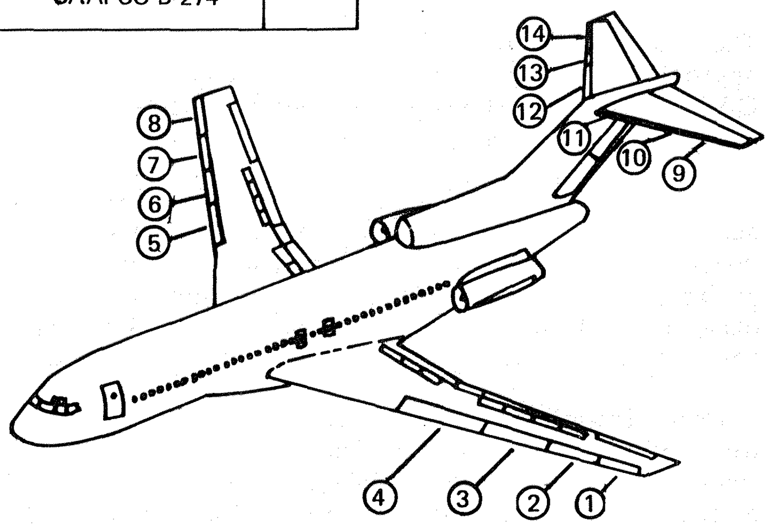
4.3.2 Delta Air Lines

Delta Air Lines (DL) domestic route structure is heavily oriented toward serving the eastern half of the United States, with some routes extending to the West Coast. A large portion of their fleet is made up of twinjet and trijet aircraft used in short-to-medium range service. These aircraft experience leading-edge erosion

and, therefore, DL was interested in a durable surface coating that would alleviate the erosion problem and, hopefully, show some drag benefits from smooth leading edges.

In November 1979, CAAPCO and Chemglaze were applied to the leading edges of the horizontal tail and wing leading-edge slats of Delta 727 number 474. The coating configuration is shown in Figure 25. The configuration met DL requirements for gray coatings on the wing slats and a wash primer applied to the aluminum substrate to facilitate removal of the coatings, following the evaluation.

Right-hand side of airplane			
Item	Wash primer	Coating	Color
5	Hughson 9924	CAAPCO B-274	Gray
6	Hughson 9924	Chemglaze M413	
7	Hughson 9924	Chemglaze M413	
8	Hughson 9924	CAAPCO B-274	
12	Hughson 9924	Chemglaze M313	Black
13		Uncoated	
14	Hughson 9924	CAAPCO B-274	



Left-hand side of airplane			
Item	Epoxy primer	Coating	Color
1	BMS 10-79	CAAPCO B-274	Gray
2	BMS 10-79	Chemglaze M413	
3	BMS 10-79	Chemglaze M413	
4	BMS 10-79	CAAPCO B-274	
9	BMS 10-79	Chemglaze M313	Black
10	–	Uncoated	
11	BMS 10-79	CAAPCO B-274	

Figure 25. Delta Air Lines Surface Coatings Configuration

The configuration allows certain other data to be obtained:

- Comparison of gray coatings on the wing with black coatings on the horizontal tail.

- Comparison of the coating-primer bond, using a wash primer and/or an epoxy primer (epoxy primer was applied over the wash primer on the left-hand side of the airplane).

- Evaluation of the effect of leading-edge radius (spanwise location) on erosion severity.

- Comparison of erosion rate of uncoated leading edge (horizontal-tail sections 10 and 13) with coated leading edges.

4.3.2.1 Coating Application Procedures

Parts to be coated were removed from the airplane and transferred to the paint shop, where they were placed leading-edge-up on sawhorses. DL maintenance personnel prepared the surfaces, and applied primer and coatings. No special paint spray equipment was required. The following procedures were observed in surface preparation.

Surface Preparation—All areas of the slats and horizontal tail leading edges not to be coated were masked with heavy paper and masking tape. Surface preparation for the areas to be coated was as follows:

- Solvent clean using 3M Doodlebug pads and methyl ethyl keytone (MEK).

- Brush or mop a solution of one part Intex 820 (alkaline cleaner) mixed with 15 parts water on leading-edge surfaces, agitating while wet with cleaner. Rinse thoroughly with water until no alkalinity remains in rinse water (check with pH paper).

- Apply Turco WO-1 (phosphoric acid etchant) keeping the surfaces wet for 3 to 5 minutes. Rinse thoroughly with water (as above).

- Manually chemically treat surfaces using Turco 4848-265, keeping the surfaces wet for 2-5 minutes. Thoroughly rinse treated surfaces with water (as above).

Primer Application—All parts to be coated (fig. 25) were primed with Hughson 9924 wash primer to facilitate coating removal at the end of the flight service evaluation. Right-hand parts, slats 1 through 4 and horizontal-tail sections 9 and 11, also were over-primed with BMS 10-79, Type II epoxy primer to provide a comparison of surface coating/primer bond strengths of left-hand and right-hand opposite parts. A standard suction cup spray gun (such as shown in fig. 26) was used to apply the primers. Figure 26 shows the wash primer being sprayed on the leading edge of a slat (area above white masking tape).

Hughson 9924 Wash Primer

- Mix equal volumes of Part A and Part B. Allow to stand 15 minutes before using. Thin with MEK if necessary.

- Apply in a single wet pass with 50% overlap during progressive coverage. Wet film thickness should be 0.057 to 0.114 mm (2.25 to 4.5 mils) to produce a dry film thickness of 0.006 to 0.013 mm (0.25 to 0.50 mils). Do not exceed 0.006 mm (0.50 mils). Desired thickness is obtained when film is continuous, but is mottled and translucent in appearance.

- Allow primer to dry one hour before overcoating.

BMS 10-79 Type II Epoxy Primer

- Shake base and curing solutions containers inverted for 20 minutes before mixing.

- Mix base and curing solutions equal parts by volume.

- Apply to a dry film thickness of 0.013 to 0.020 mm (0.5 to 0.8 mils).

- Allow to dry 2 to 3 hours before applying surface coating.

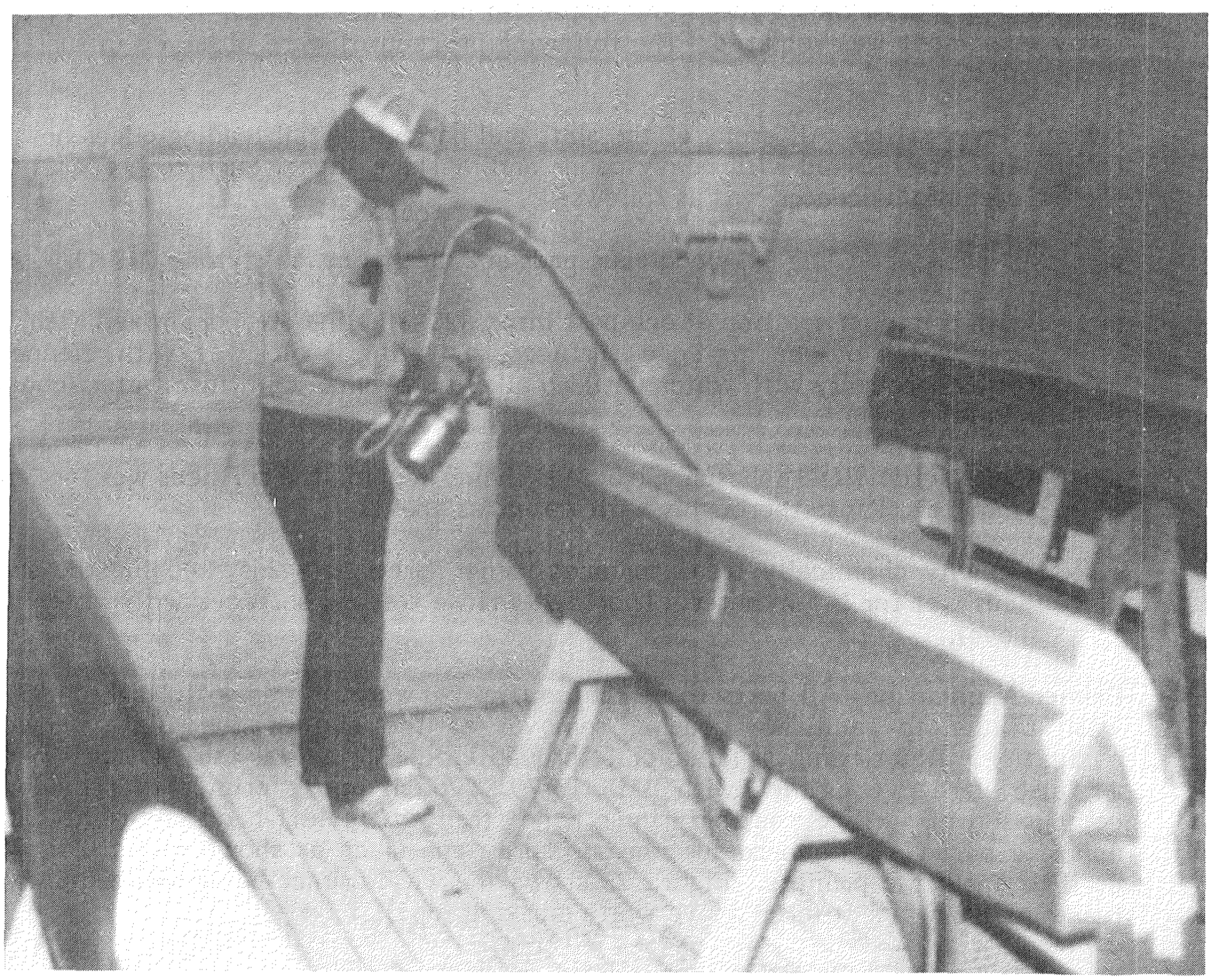


Figure 26. Wash Primer Being Sprayed on Wing Leading-Edge Slat

Coating Application—As indicated in Figure 25, gray coatings were applied to wing leading-edge slats to blend with the color of adjacent areas of the wing. Gray Chemglaze M413 was substituted for the equivalent black M313 to meet this requirement. Black CAAPCO B-274 was modified to a gray color by the addition of pigment. Black CAAPCO B-274 and Chemglaze M313 were applied to the removable sections (9, 11, 12, and 14) of the horizontal tail leading-edge. The fixed leading-edge sections at midspan (10 and 13) were left uncoated to provide an indicator of the erosion environment in which the airplane was flying.

The coatings were applied to obtain a 0.25 to 0.36 mm (10 to 14 mil) thickness at the leading edge, tapering to a reduced thickness at the aft edges. This was accomplished by sweeping the spray gun directly over and along the leading edge, as shown in Figure 27. Tape strips attached adjacent to the coated areas provided coating thickness samples that were measured by micrometer after the coatings had cured. Results are shown in Table 6.

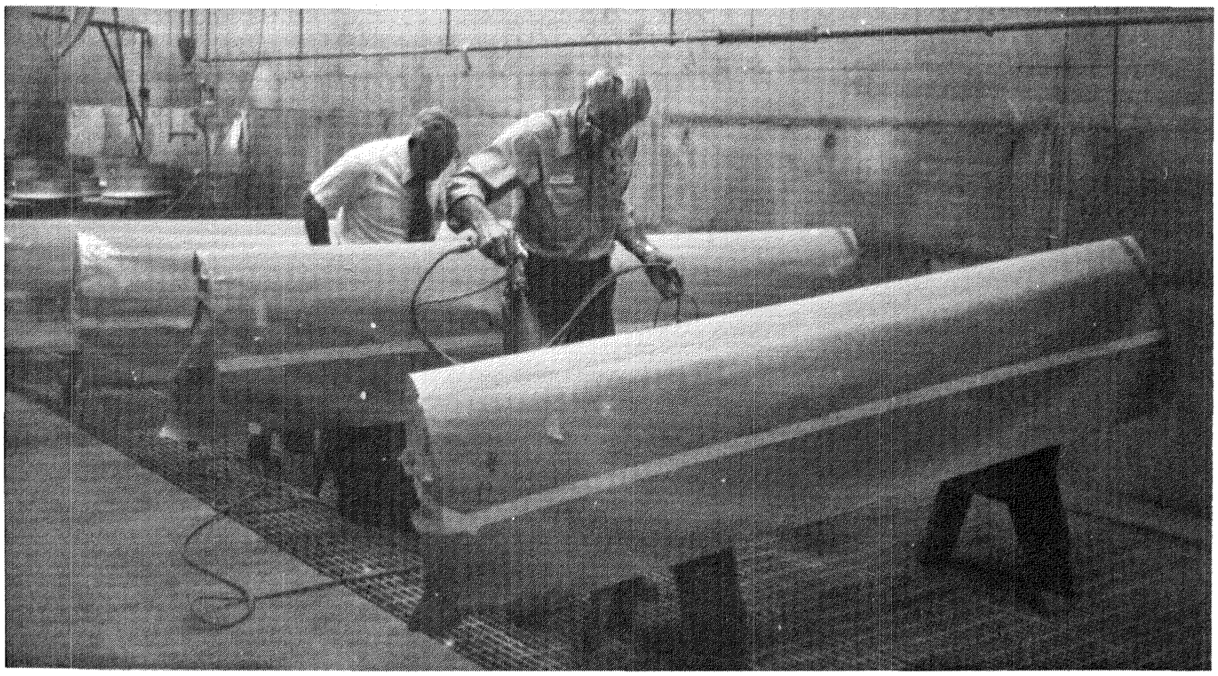


Figure 27. Surface Coating Being Sprayed Onto Wing Leading-Edge Slat

Table 6. Coating Thicknesses

Coated part	Measured at	Coating thickness, mm	(mil)
Slat No. 1	Leading edge	0.28	(11)
Slat No. 2	Aft edge	0.17	(6.5)
Slat No. 3	Leading edge	0.27	(10.5)
Slat No. 5	Leading edge	0.33	(13)
Slat No. 6	Aft edge	0.15	(6)
Horizontal tail No. 9	Leading edge	0.33	(13)
Horizontal tail No. 11	Leading edge	0.33	(13)
Horizontal tail No. 12	Leading edge	0.34	(13.5)
Horizontal tail No. 14	Leading edge	0.32	(12.5)

CAAPCO was applied in eight coats, with approximately 15 minutes drying time between coats. The first four coats were laid down with a single pass of the spray gun, and the last four with a double pass (sprayed twice without any intervening drying period).

Chemglaze M413 was applied to the slats with a pressure cup spray gun after unsuccessful attempts to thin it to the desired viscosity of 25-28 seconds, Zahn No. 2 cup (time to drain a cup with a hole of specified diameter in the bottom). Unthinned M413 was applied in three, multiple-pass coats, with 1 hour and 1 hour 35 minute drying times between coats. The Chemglaze M313 applied to the horizontal tail leading-edge had a lower viscosity (unthinned) and was applied in six coats with a suction cup spray gun. A drying time of 1 hour 20 minutes was allowed between the first and second coats, and 1 hour for each subsequent coat.

Masking tape was removed from all parts within a few minutes of completion of the final coat, before a high film strength had developed. The tape was pulled in a direction about 45 deg from the surface and downward about 45 deg from the tape line, as shown in Figure 28. No edge-lifting of the coatings occurred when tape was removed in this manner.

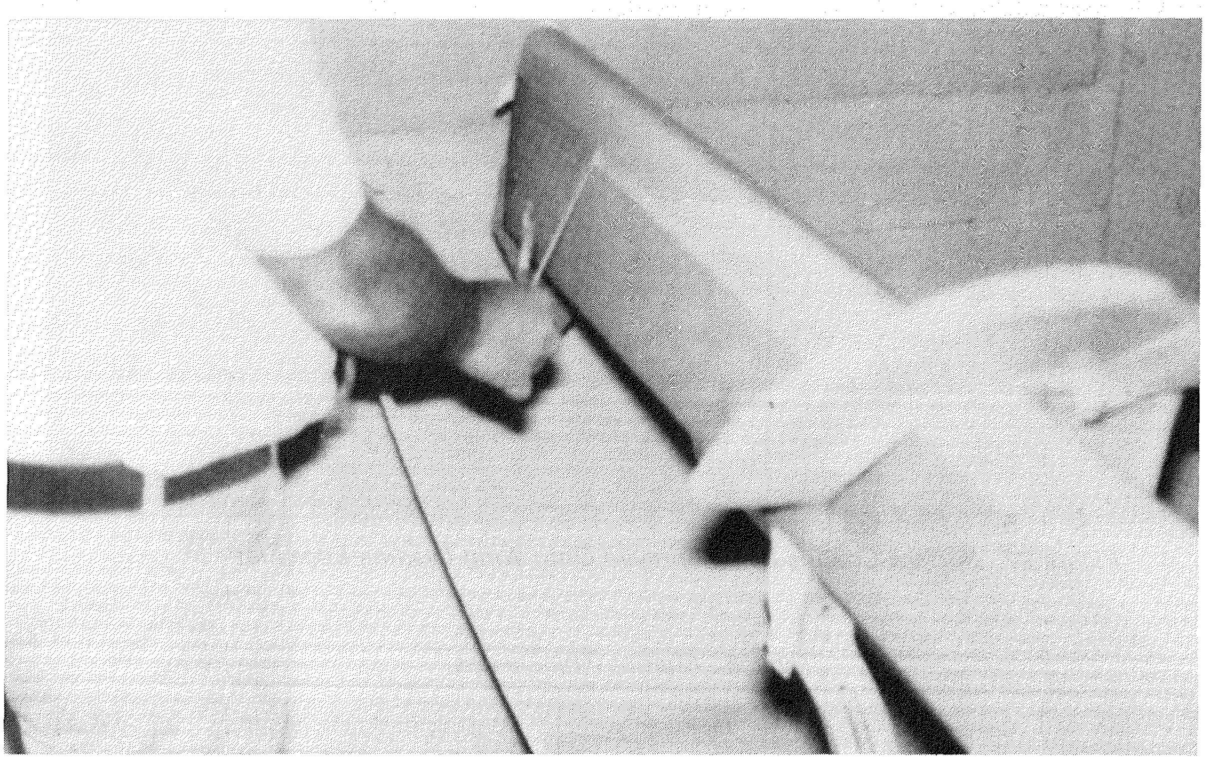


Figure 28. Method of Removing Masking Tape

Figure 29 shows the end of one of the coated horizontal tail leading-edge sections after curing. The several small light spots are reflections from overhead lighting. The smooth, high gloss surface is typical of all the coated parts—a benefit from doing the work in the relatively clean atmosphere of a paint shop with controlled air circulation.

Figure 29. Horizontal Tail Leading Edge—Typical Smooth, Glossy Coating Surface

4.3.2.2 Status Reporting

The flight service evaluation of coatings that began in November 1979 will continue for 1 year or longer, depending on condition of the coatings at the end of that time. DL personnel will make a visual inspection of the coatings at approximately 1-month intervals and report any change in their condition to the Contractor. Photos will be taken, when possible, to record significant changes. Maintenance and repair of the coatings will be done when deemed necessary by Delta, and records of maintenance labor hours and material costs will be made available to the Contractor.

4.3.3 Continental Airlines (Domestic)

Upon completion of the flight service evaluation (discussed in par. 4.3.1), the airplane (727 No. N18479) went into scheduled maintenance. Surface coatings were removed and reapplied in the configuration shown in Figure 30. The application to wing leading-edge slats was the same as for the previous flight service evaluation, however, the horizontal tail leading-edge application was modified as shown in Figure 31. Only the outboard removable leading-edge panel (about 40% of the span) was coated in three, 0.92-m (3-ft) sections separated by a 7.6-cm (3-in) uncoated strip. The right-hand panel was pre-coated in the Contractor's laboratory with Chemglaze M313 on the outboard end, Astrocoat on the center area, and CAAPCO B-274 on the inboard end, and shipped to Continental Airlines for installation on the airplane. The three sections of the left-hand outboard panel were coated in the same pattern with CAAPCO B-274.

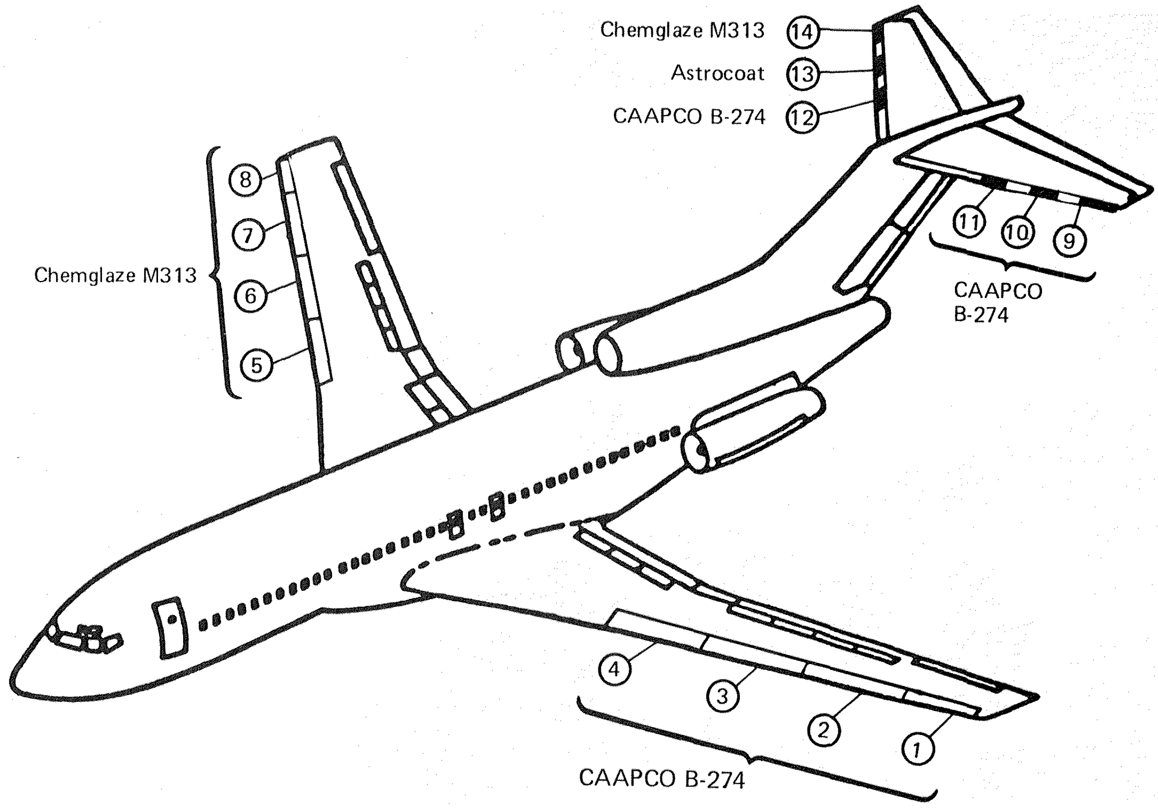


Figure 30. Continental Airlines Surface Coatings Configuration

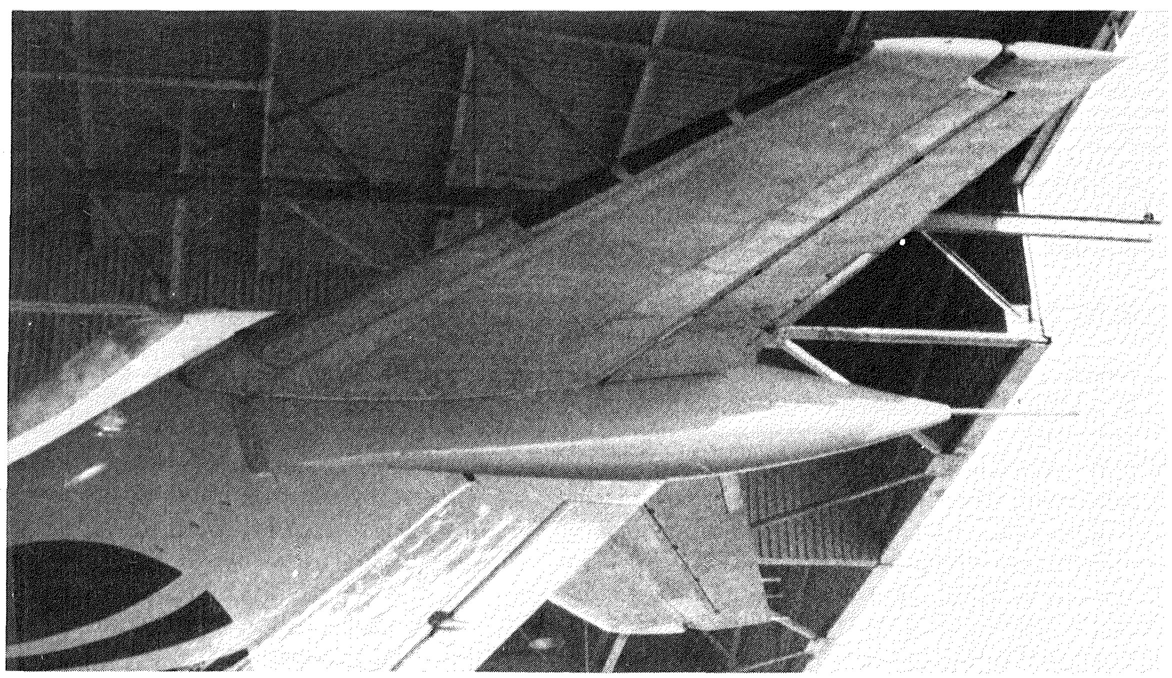


Figure 31. Horizontal-Tail Coating Configuration

The airplane with the re-coated panels returned to commercial service in late December 1979. It will be flown in the Continental Airlines (CA) domestic route system for at least one year, during which time condition of the coatings will be periodically monitored and touch-up repairs will be made, as necessary.

4.3.3.1 Application Procedure

Procedures used in the application of coatings to the Delta Air Lines 727 (par. 4.3.2) were followed, with some exceptions, in the Continental Airlines application. Differences that might have some effect on the life of the coatings are discussed below.

Surface preparation began with the removal of the old coatings using an acid stripping agent (Inland 561A). The surfaces were then masked and cleaned with an abrasive pad (Scotchbrite) and water until a "water breakfree" surface was achieved. An alkaline cleaner, recommended for this step in surface preparation, was not used. After cleaning, the surfaces were alodined with Alodine 1200.

An epoxy primer was applied using two passes of a spray gun. The primer (De Soto 513X340) was equivalent to BMS 10-79, except that it is modified for use in electrostatic spray equipment. No difference in bond strength should result.

All wing leading edge slats and the left-hand, outboard, horizontal tail leading edge were prepared and coated while installed on the airplane. Slats 1 and 5 were removed from the airplane for repair, then reinstalled prior to coating. The typical CAAPCO application consisted of 10 coats. The first coat was laid with a single pass of a spray gun, and all subsequent coats with double passes. The final coat contained CAAPCO modified to provide greater protection from ultra violet ray exposure. Approximately 15 minutes drying time was allowed between coats. Chemglaze was applied to right hand slats in four coats. Drying time between first and second coats was 1 hour 35 minutes, nearly 18 hours between second and third coats, and 2 hours between third and fourth coats. The abnormally long interval between second and third coats was to allow other priority maintenance to take place on schedule.

The airplane remained in the CA maintenance hangar several days after the coatings were applied while other scheduled maintenance was being completed. This allowed the coatings to be thoroughly cured before being exposed to the flight environment. Figures 32 and 33 show a general view and a closeup of the coated wing leading-edge slats. Figure 34 is a closeup of the left-hand outboard horizontal tail coatings, showing the typical smooth, high-gloss character of the coated surfaces.

4.3.3.2 Status Reporting

The airplane with the coated panels began flying in the CA domestic route system 20 December 1979. Visual inspections of the coatings will be made at approximate 30-day intervals and their condition reported. Any significant change in coating condition will be photographed as a part of the reports. Touch-up maintenance will be performed as necessary to preserve the general external appearance of the airplane. Maintenance labor hours and materials costs will be recorded. The flight service evaluation will continue at least 1 year.

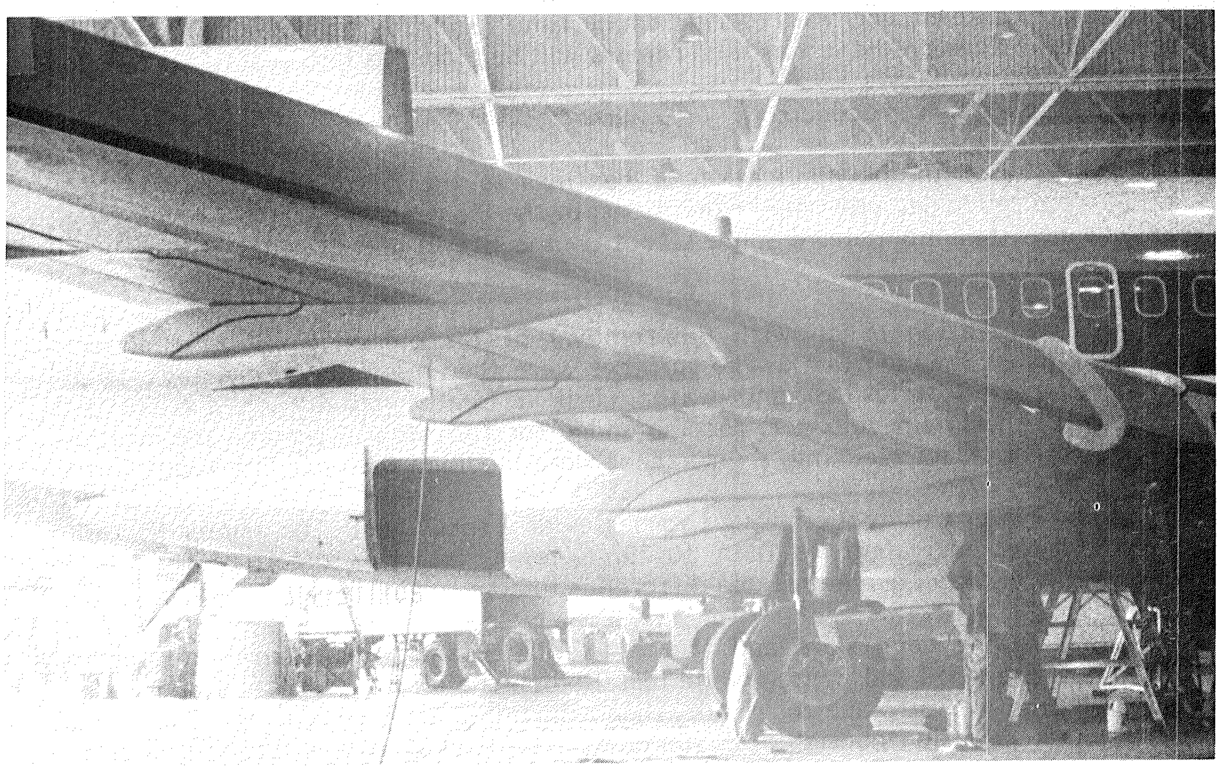


Figure 32. Wing Leading-Edge Slat Coating

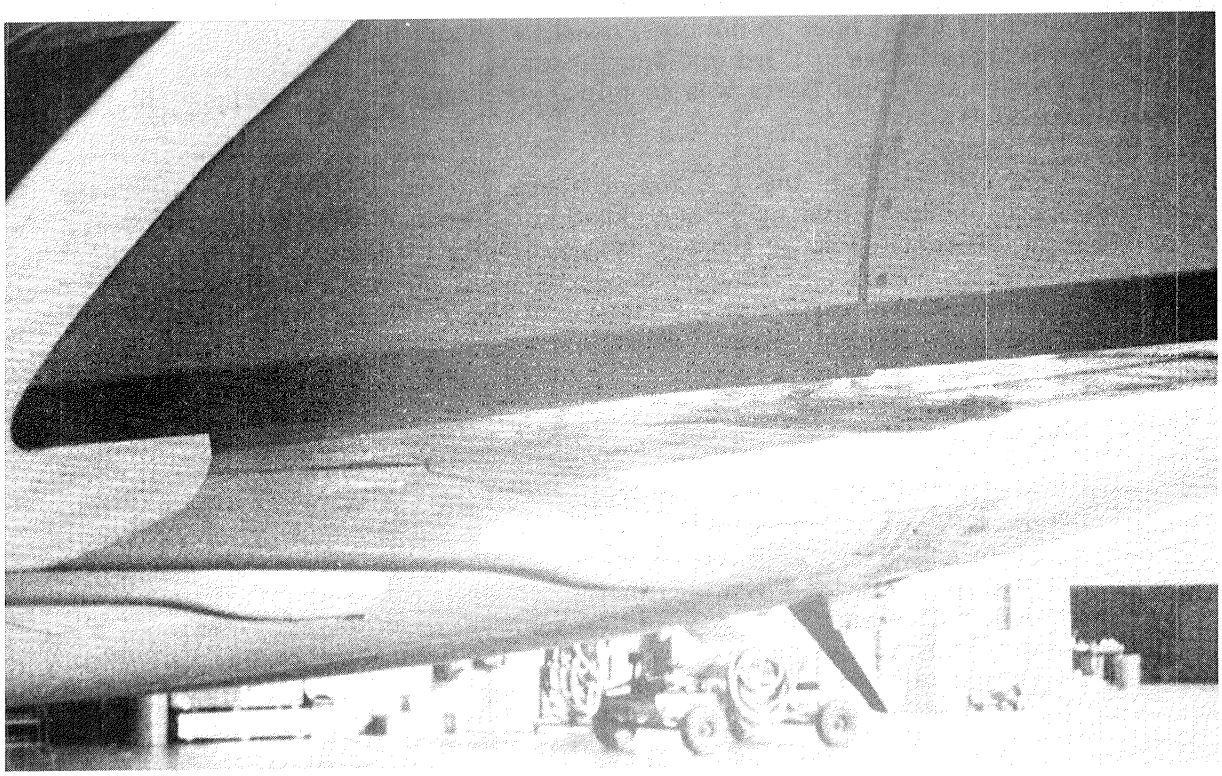


Figure 33. CAAPCO B-274 Coating, Slats 3 and 4

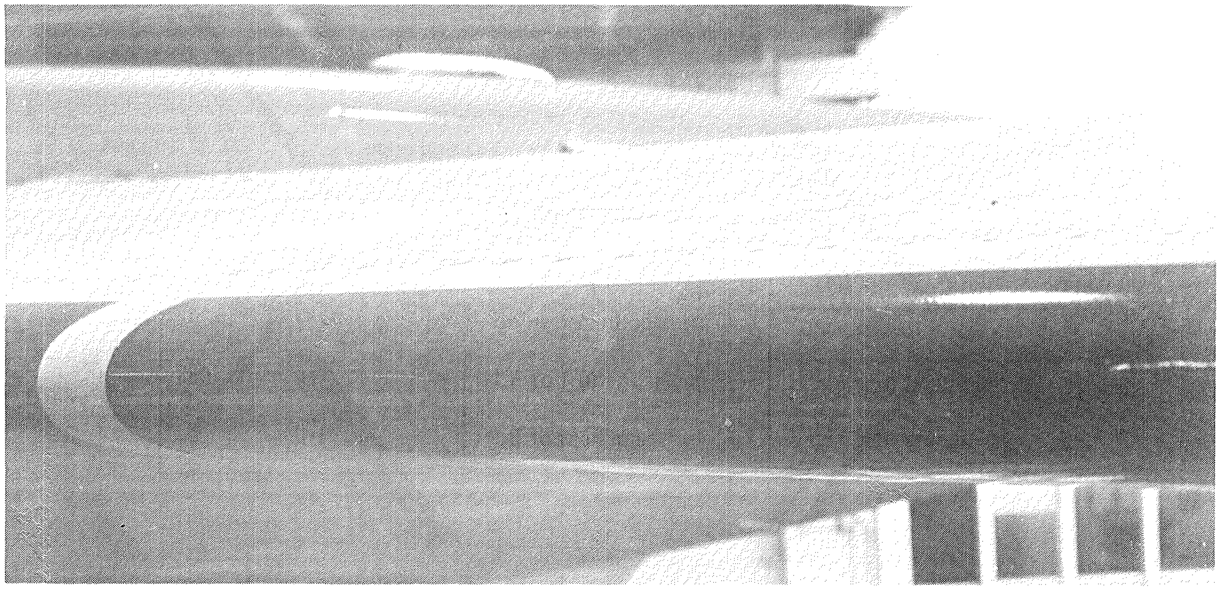


Figure 34. Coated Leading Edge, LH Horizontal Tail

4.4 COST/BENEFITS ANALYSIS

The cost/benefits analysis reported in Reference 1 was reviewed and updated to reflect changes in material, labor and fuel costs, and to reflect results from the Air Micronesia flight service evaluation. The methodology used in the Reference 1 analysis was followed, as were the fleet operating assumptions repeated below:

Fleet size	2000 airplanes
Utilization	2500 hours/year
Mission range	1611 km (870 nmi)
Block time	2.33 hr
Trips per day	3

The analysis was based on different amounts of coating coverage on a 727-200 airplane, as defined in Table 7 and illustrated in Figure 35.

Astrocoat was not included in the cost/benefits analysis because it was not included in the Air Micronesia flight service evaluation. Conclusions drawn from that evaluation produced the most significant change to the updated cost/benefits analysis.

Table 7. Coating Application Areas

Area covered		
Case	Wing	Empennage
I	Slats, flaps, and leading edge (LE) to 5% chord on upper inboard surface	LE to 5% chord
II	LE to front spar	LE to front spar
III	LE to rear spar	LE to rear spar

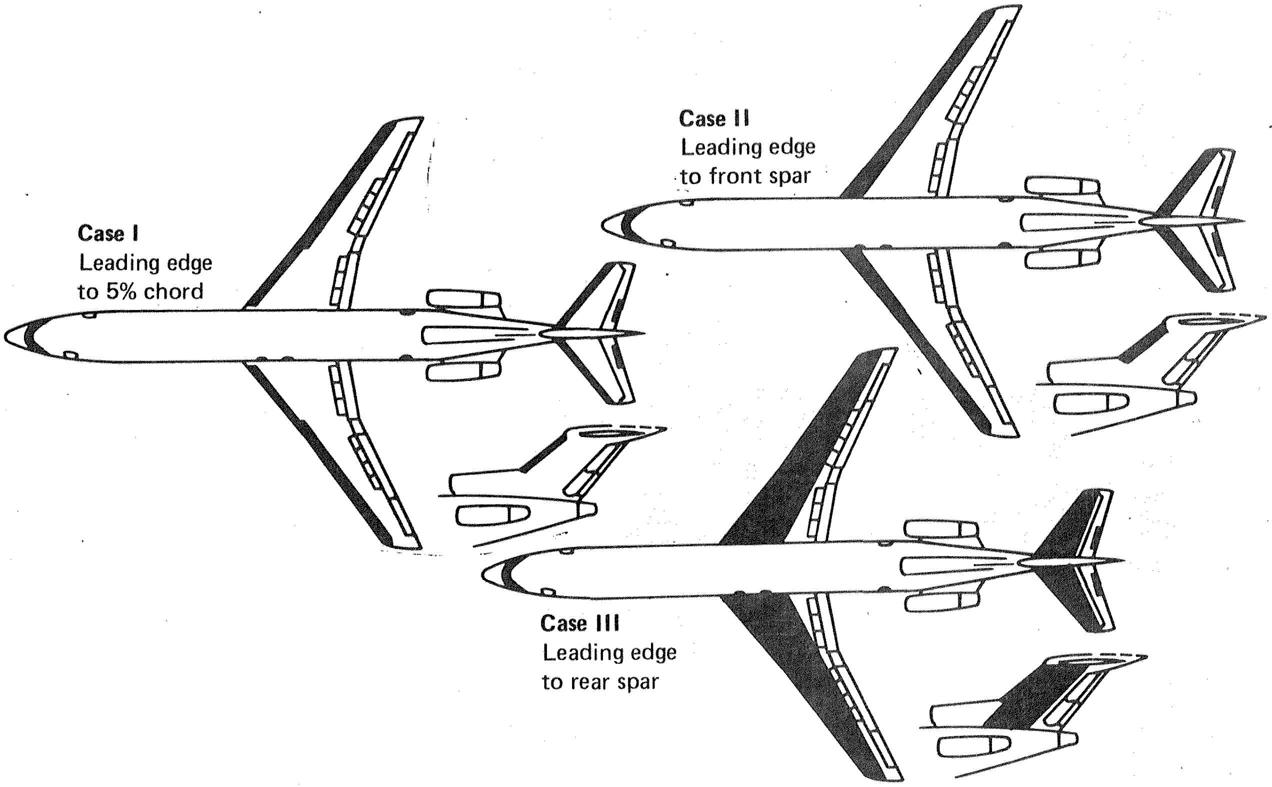


Figure 35. 727-200 Coating Application Areas

4.4.1 Application Costs

All costs associated with the coatings were calculated in 1980 dollars. The Air Micronesia evaluation showed Chemglaze M313 to be as durable as CAAPCO B-274, therefore, its survival life was increased from 2790 hours (Reference 1, Table 27) to equal the 6000 hour life projected for CAAPCO in a normal operating environment. This important change resulted in fewer field leading-edge recoat applications for Chemglaze (Table 8) than assumed in the previous analysis, and lower total cycle costs.

Table 8. 45,000-hr Cycle Requirements for Paint and Coating Applications

Applications	Paint application			CAAPCO application			Chemglaze application		
	Case I	Case II	Case III	Case I	Case II	Case III	Case I	Case II	Case III
Factory applications									
Number of applications	—	—	1	1	1	1	1	1	1
Flow hours	—	—	63	84	84	84	74	74	74
Labor hours	—	—	56	55	74	174	39	48	96
Field leading-edge recoat	a	a	a						
Number of applications	17	17	17	6	6	6	6	6	6
Flow hours	—	—	—	84	84	84	74	74	74
Labor hours	4	4	4	64	64	64	48	48	48
Field total recoat	b	b	b						
Number of applications	—	—	2	2	2	2	2	2	2
Flow hours	—	—	63	84	84	84	74	74	74
Labor hours	—	—	98	64	90	231	48	64	153

[a]Field leading-edge buffing. [b]Field total repaint.

The coverage and weight of each of the painting/coating components were reviewed, and in some instances, revised. Based on the Skydrol exposure tests, a topcoat of polyurethane enamel was added to the upper-surface inspar areas for Case III. This change to the coating system was based on the speculation that the dual coating would offer satisfactory corrosion protection, as well as improving the resistance to Skydrol. The resulting areas and weights are shown in Table 9.

Table 9. Painting and Coating Areas and Applied Material Weights

	Case I		Case II		Case III	
	Area, m^2 (ft^2)	Weight, kg (lb)	Area, m^2 (ft)	Weight, kg (lb)	Area, m^2 (ft^2)	Weight, kg (lb)
Painting	a	a	a	a		
Primer	—	—	—	—	174.38 (1877)	5.11 (11.26)
Corogard	—	—	—	—	55.00 (592)	4.70 (10.36)
Polyurethane enamel	—	—	—	—	119.38 (1285)	6.41 (14.14)
Total	—	—	—	—	—	16.22 (35.76)
Coating	36.23 (390)	1.06 (2.34)	65.31 (703)	1.89 (4.22)	239.69 (2580)	7.02 (15.48)
Primer						
Coating[b]	36.23 (390)	12.38 (27.30)	65.31 (703)	18.75 (41.39)	239.69 (2580)	36.18 (79.77)
Polyurethane enamel					174.38 (1877)	9.37 (20.65)
Total	—	13.44 (29.64)	—	20.64 (45.61)		52.57(115.90)
Weight differential (coating-painting)	—	13.44 (29.64)	—	20.64 (45.61)		36.35 (80.14)

[a]Paint, not applied to Cases I and II area on baseline 727-200.

[b]Coating thickness 0.30 mm (0.012 in) from leading edge to 5% chord, tapered to 0.09 mm (0.0035 in) from 5% chord to front spar and 0.09 mm (0.0035 in) from front spar to rear spar.

The effect of increased airplane operating empty weight (OEW), due to coatings, on estimated annual fuel burn for a 727-200 is shown in Figure 36. Cases I and II represent the addition of coatings to leading-edge areas that are normally unpainted; Case III represents a weight increment of coatings above that of the normal paint system applied to the inspar areas of wing and empennage.

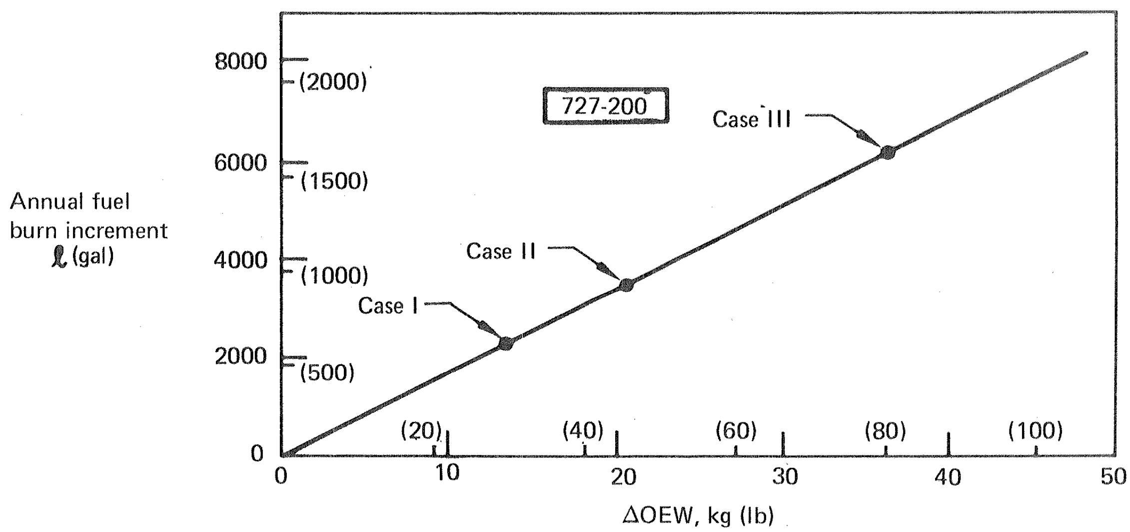


Figure 36. Fuel Burn Sensitivity to Weight

Table 10 shows the cost per application of each painting/coating application for the three study cases. Material costs were based on large quantity purchase prices quoted by vendors.

Table 10. Material Costs per Application (727-200)

	Case I			Case II			Case III		
	Component cost , $	Total cost, $	Material cost difference coat-paint, $	Component cost, $	Total cost, $	Material cost difference coat-paint, $	Component cost, $	Total cost, $	Material cost difference coat-paint, $
Painting									
Primer	—	—	—	—	—	—	244	—	—
Corogard	—	—	—	—	—	—	308	—	—
Polyurethane enamel	—	—	—	—	—	—	218	770	—
Coating									
Primer	51	—	—	91	—	—	335	—	—
Polyurethane enamel	—	—	—	—	—	—	319	—	—
Coating									
CAAPCO	702	753	753	1,266	1,357	1,357	4,644	5,298	4,528
Chemglaze	218	269	269	394	485	485	1,445	2,099	1,329

4.4.2 Benefits Analysis

The potential benefits of applying a coating to the leading-edge area on a 727-200 wing and empennage, and a coating in lieu of paint to the inspar area, are shown in Figure 37. The actual benefits realized will vary for individual airplanes, depending upon the condition of the surfaces covered by the coatings. The coatings are capable of masking small surface anomolies such as misaligned fastener heads and small gaps in skin butt joints, and will protect against leading-edge erosion. Drag measurements from flight and/or wind tunnel testing of representative surfaces are necessary* to estimate potential drag benefits (fuel savings) from individual applications.

The curves in Figure 37 do not reflect any benefits from reduced surface maintenance costs, other than periodic buffing of uncoated leading edges to remove erosion pitting. Airlines with severe erosion problems eventually are faced with reskinning or replacement of leading edge parts. With this conservatism, the application of coatings only to leading edges (Cases I and II) to conserve fuel would not be beneficial. For the Case III application, an airplane drag reduction greater than 0.3 to 0.5% would produce benefits to the airline, depending upon the price of fuel and the coating used.

*At this writing, a drag-measurement flight test is being planned to investigate the possible drag benefits from surface coatings.

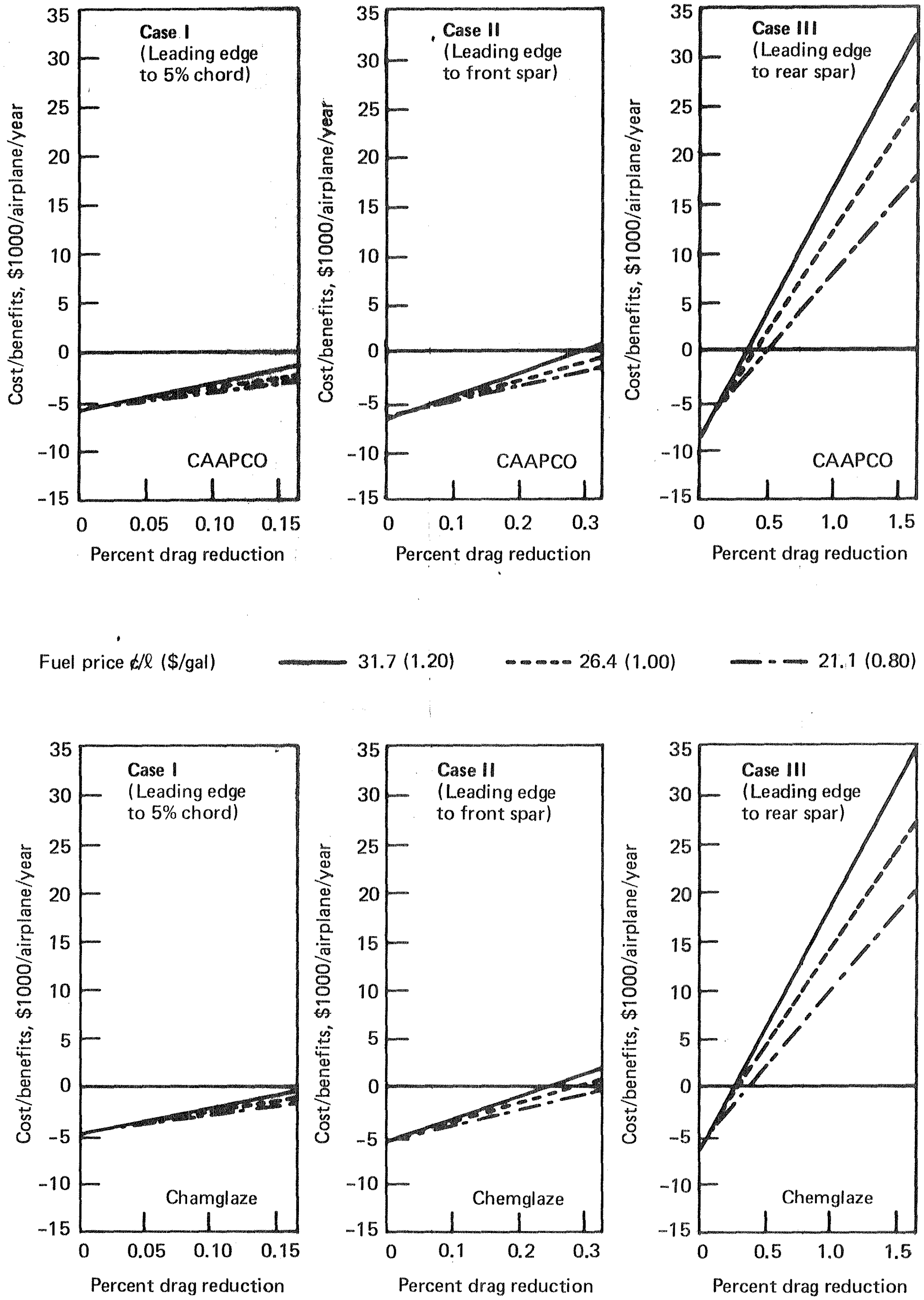


Figure 37. Potential Cost/Benefits of Coatings

5.0 CONCLUSIONS AND RECOMMENDATIONS

The conclusions stated below are an extension of the conclusions of Reference 1, gained from results of a rigorous flight service evaluation and additional laboratory testing of promising candidate materials. Recommendations are based on the premise that the development of surface coating technology should be pursued to the extent that it can be offered as an option for airline fleet application.

5.1 CONCLUSIONS

- Elastomeric polyurethane coatings are effective in the prevention of leading-edge erosion. A flight service evaluation in a severe erosion environment showed only minor deterioration of CAAPCO B-274 and Chemglaze M313 coatings during the first 2000 flight hours. No maintenance or repair of coatings was performed during the evaluation. Astrocoat was not evaluated.

- At the conclusion of the 14-month flight service evaluation CAAPCO appeared to have a minor reaction to the effects of ultraviolet (UV) radiation. No UV effects on Chemglaze were apparent.

- In laboratory tests, CAAPCO demonstrated the greatest resistance to synthetic Type IV hydraulic fluid exposure. Astrocoat showed the least resistance.

- A topcoat of BMS 10-60 polyurethane enamel over any of the three surface coating materials (CAAPCO, Chemglaze, Astrocoat) provides protection from synthetic hydraulic fluid. The topcoat, however, is not durable in areas of high erosion.

- Dual coating systems, consisting of a topcoat of BMS 10-60 and a basecoat of an elastomeric polyurethane, exhibited good adhesion when subjected to flexibility tests and tape adhesion tests.

- Coating life is very much a function of the care exercised during the application process. Thorough cleaning of the substrate, use of proper solvents and primer, and adherance to proper coating viscosities and drying times are essential to producing a durable coating.

- Coating repair is feasible. Again, care must be exercised during the repair process to ensure good results.

- Limited laboratory experiments with films and polysulfide adhesives produced moderate peel strengths in the 1.04-1.75 kg/cm (5.8-9.8 lb/in) range with Tradlon, Kynar, and Kapton films. Tra-Con 2133 adhesive with Kynar film produced the highest peel strength of 2.86-3.27 kg/cm (16.0-18.3 lb/in), which meets the criterion established in Reference 1, of 1.79 kg/cm (10.0 lb/in). It was not determined if these bond characteristics change after prolonged environmental exposure.

- The cost of coatings applied to leading edges for erosion protection will not be offset by reduced fuel costs. Potential drag benefits (fuel savings) from more extensive application of coatings are not known. It was estimated that if a drag reduction of 0.3-0.5% resulted from the application of coatings to

a 727-200 wing and empennage, from leading edge to rear spar, the cost of coatings would be offset by fuel savings.

5.2 RECOMMENDATIONS

- The recent escalation of airline fuel costs has focused attention on methods of reducing airplane drag. Flight and/or wind tunnel tests should be conducted to determine if there are potential drag benefits from the application of surface coatings. Measurements should be made relative to various baseline (uncoated) surface conditions.

- Tests should be conducted to determine the characteristics of coated surfaces exposed to icing conditions, and the effect of coatings on thermal anti-icing system efficiency.

- Tests should be conducted to assess the characteristics of coated surfaces exposed to atmospheric electrical phenomena.

- Tests should be conducted to investigate the corrosion-inhibiting properties of a dual coating system composed of an elastomeric polyurethane base and a polyurethane enamel topcoat.

6.0 REFERENCES

1. NASA Contractor Report 158954, "Aircraft Surface Coatings Study," Boeing Commercial Airplane Company, January 1979.

2. Federal Test Method Standard 141a, Method 6301.1 (adhesion testing), September 1965.

3. American Society for Testing and Materials, D903, (peel testing), reapproved 1978.

4. Federal Test Method Standard 141a, Method 6221, (flexibility testing), September 1965.

5. "Climates of the World," U.S. Department of Commerce, Environmental Data Service, January 1969.

APPENDIX A
TEST RESULTS

TABLES

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APPENDIX A
TEST RESULTS

Appendix A contains results of tests conducted to determine exposure limits of liquid and film coatings to synthetic-type hydraulic fluids such as Skydrol and Hyjet Type IV, and liquid coatings to erosion from rain. Seven liquid coating systems were tested, including CAAPCO B-274, Chemglaze M-313 and Astrocoat; three dual coatings that incorporated BMS 10-60 as a topcoat; and BMS 10-60 only. Three film coatings (Tradlon, Kynar and Kapton) were tested in combination with eight adhesives. A fourth film, adhesive-back UHMW Polyolefin, also was tested.

Tables A-1, -2, -3, and -4 summarize the effect of exposure to Skydrol by simulating conditions of puddling, spillage, drip, and immersion. A baseline (unexposed) control experiment was performed simultaneously with all tests. After exposure, specimens were subjected to pencil hardness tests per BMS 10-79, procedure 7.2.5 (included in Appendix B of ref. 1). The test consists of moving square-tipped pencils of varying hardnesses across the surface, while inclined into the surface at 45 deg. Pencils of increasing hardness are tried until the pencil lead digs into and scuffs the surface. The following identification codes were used and are listed in order of increasing pencil hardness: 6B-2B, B, HB, F, H, 2H-6H. Adhesion tape tests were performed on those specimens that were not severely attacked. Table A-4, the Skydrol immersion test, shows the results of specimens tested for pencil hardness and peel strength. Peel strength was measured by pulling a free tab of the coating at a 180-deg angle and peeling parallel to surface.

Table A-5 is a summary of the baseline (unexposed) pencil hardness test for the Skydrol test series.

Tables A-6 and A-7 are results of the rain erosion tests for conditions of 179 m/s (400 mph) and 224 m/s (500 mph). The tests were conducted at the Air Force Materials Laboratory, Wright-Patterson AFB. Coatings that performed well in the Skydrol tests were selected for the rain erosion test to determine durability.

Table A-8 contains film peel strength data for the four test films under three conditions: Skydrol immersion, water immersion, and control (no immersion).

Table A-1. Skydrol Puddling Tests

Coating / Exposure time	Pencil hardness and adhesion													
	1 CAAPCO B-274		2 CAAPCO B-274 plus BMS 10-60 Type II		3 Chemglaze M313		4 Chemglaze M313 plus BMS 10-60 Type II		5 Astrocoat Type I		6 Astrocoat Type I plus BMS 10-60 Type II		7 BMS 10-60 Type II	
	Pencil No.	Elapsed days	Pencil No.	Elapsed days	Pencil No.	Elapsed days	Pencil No.	Elapsed days	Pencil No.	Elapsed days	Pencil No.	Elapsed days	Pencil No.	Elapsed days
Baseline (unexposed)	6H	0	6H	0	6H	0	5H	0	6H	0	5H	0	2H	0
	6H	7	6H	7	6H	2	5H	2	6H	3	5H	1	2H	1
	6H	10	6H	10	6H	2	5H	5			5H	4	2H	4
	5H	35	H	35			2H	30			2B	29	2H	29
Tape test	Passed		Passed		Passed		Passed		Passed		Passed		Passed[a]	
5 min	6H	0	6H	0	6B	0	5H	0	6H	0	5H	0	3H	0
	6H	1(hr)	6H	0	6B	2	3H	2	H	3	3H	1	H	1
	6H	7	6H	7	Coating attacked		2H	5	Coating attacked		H	4	HB	4
	6H	10	6H	10			2H	30			2B	29	HB	29
	5H	35	2H	35										
Tape test	Invalid[b]		Passed				Passed		Passed		Invalid[b]		Passed[a]	
1 hr	6H	0	6H	0	6B	0	5H	0	6H	0	5H	0	3H	0
	6H	4	6H	4	6B	2	3H	2	H	3	3H	1	F	1
	6H	7	5H	7	Coating attacked,		3H	5	Coating attacked		F	4	HB	4
	H	32	H	32	test terminated		H	30			2B	29	HB	29
Tape test	Invalid[b]		Passed				Passed		Not tested		Passed		Passed[a]	
4 hr	6H	0	6H	0			5H	0	5B	0	5H	0	3H	0
	6H	4	6H	4			3H	1	5B	3	2H	1	F	1
	6H	7	5H	7			2H	4	Coating attacked		HB	4	HB	4
	H	32	H	32			H	29			2B	29	HB	29
Tape test	Invalid[b]		Passed				Passed		Not tested		Passed		Passed[a]	
8 hr	6H	0	6H	0			5H	0	6B	0	H	0	H	0
	6H	4	6H	4			3H	1	6B	3	F	3	HB	3
	5H	7	5H	7			2H	4	Coating attacked		HB	7	HB	7
	H	32	2H	32			H	29			2B	28	HB	28
Tape test	Invalid[b]		Passed				Passed		Not tested		Passed		Passed[a]	
2 days	6H	0	6H	0			2H	0	6B	0	HB	0	H	0
	6H	1	6H	1			H	3	Coating attacked		2B	2	HB	2
	5H	4	5H	4			HB	7			3B	23	HB	23
	2B	29	2H	29			B	29			4B	25	HB	25
Tape test	Invalid[b]		Passed				Passed		Not tested		Passed		Passed[a]	
4 days	6H	0	6H	0			H	0	6B	0	HB	0	HB	0
	6H	4	6H	4			HB	4	Coating lifted		2B	2	HB	2
	3H	7	2H	7			B	25	and blistered		2B	23	HB	23
	B	32	H	32			B	27			4B	25	HB	25
Tape test	Invalid[b]		Passed				Passed		Not tested		Passed		Passed[a]	
7 days	6H	0	5H	0			F	0	6B	0	2B	0	HB	0
	3H	3	2H	3			HB	2	Coating lifted		4B	1	HB	1
	HB	26	H	26	Coating attacked,		B	21	and blistered		4B	20	HB	20
	2B	27	H	28	test terminated		B	23			4B	22	HB	22
Tape test	Invalid[b]		Passed				Passed		Not tested		Passed		Passed[a]	

[a]Passed test; however, coating lifted 1.6 mm (1/16 in) from cut line.

[b]Test invalid due to poor adhesion of tape to coating.

Table A-2. Skydrol Spillage Tests

Coating	Pencil hardness and adhesion													
	1 CAAPCO B-274		2 CAAPCO B-274 plus BMS 10-60 Type II		3 Chemglaze M313		4 Chemglaze M313 plus BMS 10-60 Type II		5 Astrocoat Type I		6 Astrocoat Type I plus BMS 10-60 Type II		7 BMS 10-60 Type II	
Exposure time	Pencil No.	Elapsed days	Pencil No.	Elapsed days	Pencil No.	Elapsed days	Pencil No.	Elapsed days	Pencil No.	Elapsed days	Pencil No.	Elapsed days	Pencil No.	Elapsed days
Baseline (unexposed)	6H	0	5H	0	6H	0	5H	0	6H	0	3H	0	3H	0
	6H	7	2H	7	6H	7	H	7	6H	7	H	7	2H	7
	6H	22	2H	23	6H	23	F	23	3H	23	HB	23	2H	23
Tape test	Passed		Passed		Passed		Passed		Passed		Passed		Passed	
5 min	6H	0	5H	0	6B	0	3H	0	H	0	H	0	2H	0
	6H	3	5H	3	5B	3	2H	3	H	3	HB	3	2H	3
	6H	22	H	23	Coating attacked		H	23	Coating attacked		B	23	2H	23
Tape test	Passed		Passed		Passed		Passed		Passed		Passed		Passed	
1 hr	6H	0	3H	0	6B	0	2H	0	H	0	HB	0	2H	0
	6H	6	2H	6	5B	6	H	6	H	6	B	6	2H	6
	6H	21	H	22	Coating attacked		HB	22	Coating attacked		2B	22	2H	22
Tape test	Passed		Passed		Invalid[a]		Passed		Passed		Passed		Passed	
4 hr	6H	0	3H	0	6B	0	H	0	H	0	HB	0	2H	0
	6H	3	2H	3	6B	3	F	3	Coating attacked		2B	3	2H	0
	6H	22	H	23	Coating attacked		HB	23	H	3	4B	23	2H	13
Tape test	Passed		Passed		Invalid[a]		Passed		Invalid[a]		Passed		Passed	
8 hr	6H	0	H	0	6B	0	HB	0	F	0	HB	0	H	0
	6H	6	H	6	6B	6	HB	6	HB	6	2B	6	H	6
	6H	21	F	22	Coating attacked		HB	22	Coating attacked		2B	22	H	22
									F	22				
Tape test	Passed		Passed		Invalid[a]		Passed		Invalid[a]		Passed		Passed	
2 days	6H	0	H	0	5B	0	HB	0	HB	0	2B	0	H	0
	6H	5	H	5	6B	5	HB	5	HB	5	2B	5	H	5
	6H	20	H	21	Coating attacked		HB	21	Coating attacked		4B	21	H	21
									HB	21				
Tape test	Passed		Passed		Invalid[a]		Passed		Invalid[a]		Passed		Passed	
4 days	6H	0	H	0	5B	0	HB	0	F	0	B	0	H	0
	6H	4	H	4	6B	1	HB	4	HB	4	2B	4	H	4
	6H	19	H	20	Coating attacked		HB	20	Coating attacked		2B	20	H	20
									F	20				
Tape test	Passed		Passed		Invalid[a]		Passed		Passed		Passed		Passed	
7 days	2H	0	H	0	6B	0	HB	0	F	0	B	0	H	0
	5H	15	H	16	6B	16	HB	16	Coating attacked		2B	16	H	16
									F	16				
Tape test	Passed		Passed		Invalid[a]		Passed		Not tested		Passed		Passed	

[a] Poor adhesion of tape, not a true test.

Note: All specimens wiped dry with cotton glove before test.

Table A-3. Skydrol Drip Tests

	Pencil Hardness and Adhesion											
Coating / Exposure time	1 CAAPCO B-274		2 CAAPCO B-274 plus BMS 10-60 Type II		3 Chemglaze M313		4 Chemglaze M313 plus BMS 10-60 Type II		5 Astrocoat Type I		6 Astrocoat Type I plus BMS 10-60 Type II	
	Pencil No.	Elapsed days	Pencil No.	Elapsed days	Pencil No.	Elapsed days	Pencil No.	Elapsed days	Pencil No.	Elapsed days	Pencil No.	Elapsed days
Baseline (unexposed)	6H 6H 5H	0 10 18	2H H H	0 10 18	5H 5H	0 10	2H F HB	0 10 18	6H 5H	0 14	HB 2B 2B	0 10 18
Tape test	Passed		Passed		Passed		Passed		Passed		Passed	
5 min	5H 3H 3H	0 0 8	H F HB HB	0 0 3 11	6B 6B	0 0	HB B 2B	0 0 17	6B	0	HB HB B 2B	0 0 9 17
Tape test	Passed		Passed		Poor adhesion		Passed		Poor adhesion		Passed	
1 hr	H H H H	0 0 3 11	H F F HB	0 0 3 11	Coating attacked, test terminated		HB HB 2B 2B	0 0 9 17	Coating attacked, test terminated		B 2B 2B 2B	0 0 8 16
Tape test	Passed		Passed				Passed				Passed	
4 hr	F F H H	0 0 3 11	H H F F	0 0 9 17			B 2B 4B 4B	0 0 8 16			2B 3B 4B 4B	0 0 2 10
Tape test	Passed		Passed				Passed				Passed	
8 hr	F F F	0 0 9	F F HB HB	0 0 8 16			2B 2B 4B 4B	0 0 2 10			5B 5B 5B 5B	0 0 2 10
Tape test	Passed		Passed				Passed				Passed	
2 days	3B 5B 4B	0 0 7	F HB HB	0 0 7			4B 5B 5B	0 0 7			5B 5B 4B	0 0 7
Tape test	Passed		Passed				Passed				Passed	
4 days	4B 5B 4B	0 0 7	F F HB	0 0 7			4B 4B 4B	0 0 7			5B 5B 5B	0 0 7
Tape test	Passed		Passed				Passed				Passed	
7 days	3B 5B 6B 5B	0 0 7 15	F F HB HB	0 0 7 15	Coating attacked, test terminated		2B 3B 4B 4B	0 0 7 15	Coating attacked, test terminated		4B 4B 5B 5B	0 0 7 15
Tape test	Passed		Passed				Passed				Passed	

Note: Initial hardness measurements of exposed coatings made with Skydrol film on surface. Coatings then wiped dry for all subsequent measurements.

Table A-4. Skydrol Immersion Tests

Coating No.	Coating	Soak period, days	Pencil hardness		180-deg maximum peel strength kg/cm (lb/in)	Remarks
			Before soak	After soak		
1	CAAPCO B-274	2	5H	HB	0 (0) 0 (0)	Cohesive failure in free film tab.
2	CAAPCO B-274 plus BMS 10-60 Type II	7	H	B	0.86 (4.8) 0.89 (5.0)	
		30	H	HB	1.05 (5.9) 1.09 (6.1)	Cohesive failure in free film tab.
4	Chemglaze M313 plus BMS 10-60 Type II	7	6B	5B	Not measured	Tab adhered to substrate, peel strength unobtainable.
		18	6B	6B	0.96 (5.4)	Cohesive failure in free film tab and also cohesive failure of M313 in peel. Peel 12.7 mm (1/2 in.) long
					0.89 (5.0)	Cohesive failure in free film tab and also cohesive failure of M313 in peel. Peel 6.4 mm (1/4 in.) long.
6	Astrocoat Type I plus BMS 10-60 Type II	7	HB	4B	1.05 (5.9)	Cohesive failure in free film tab.
					0.89 (5.0)	
		14	B	6B	0.93 (5.2)	Cohesive failure in free film tab.

Note: Coating surface blotted dry prior to pencil hardness measurements.

Table A-5. Baseline (Unexposed) Pencil-Hardness Summary

Coating / Skydrol test series	1 CAAPCO B-274 Pencil No.	Elapsed days	2 CAAPCO B-274 plus BMS 10-60 Type II Pencil No.	Elapsed days	3 Chemglaze M313 Pencil No.	Elapsed days	4 Chemglaze M313 plus BMS 10-60 Type II Pencil No.	Elapsed days	5 Astrocoat Type I Pencil No.	Elapsed days	6 Astrocoat Type I plus BMS 10-60 Type II Pencil No.	Elapsed days	7 BMS 10-60 Type II Pencil No.	Elapsed days
Puddling	6H 6H 6H 5H 2H 2H	0 7 10 35 64 224	6H 6H 6H H F F	0 0 0 35 64 224	6H 6H 6H 6H	0 2 76 219	5H 5H 5H 2H H H	0 2 5 30 76 219	6H 6H 2H 2H	0 3 13 156	5H 5H 5H 2B 4B 4B	0 1 4 29 75 218	2H 2H 2H 2H 2H 2H	0 1 4 4 4 218
Spillage	6H 6H 6H 3H 3H	0 7 23 70 138	5H 2H 2H H H	0 7 23 70 138	6H 6H 6H 6H 6H	0 7 23 70 138	5H H F HB HB	0 7 23 70 138	6H 6H 3H 2H 3H	0 7 23 70 138	3H H HB 2B 2B	0 7 23 70 138	3H 2H 2H 2H 2H	0 7 7 70 138
Drip	6H 6H 5H 5H	0 10 58 184	2H H F F	0 10 58 184	5H 6H 6H	0 58 154	2H F HB HB	0 10 58 184	6H 5H 5H	0 58 154	HB 2B 5B 6B	0 10 58 184	Not evaluated	

Table A-6. Rain Erosion Test Results—179 m/s (400 mph)

Configuration	Penetration time (min)										Total test time (min)	Post-test condition of specimen
	Percent topcoat removed[a]					Percent basecoat removed[b]						
	Initial	25	50	75	100	Initial	25	50	75	100		
B-274 plus BMS 10-60 Unexposed	35.6	—	75	85	106	102	120	—	—	—	120	Basecoat pitted throughout eroded area. Material removed down to primer on 30% of test area.
	35.6	—	75	85	105	98	120	—	—	—	120	Basecoat severely eroded and pitted. Primer showing on 40% of test area.
B-274 plus BMS 10-60 7-day Skydrol spillage	45.6	—	68	98	102	108	120	—	—	—	120	Basecoat pitted. Material removed down to primer on 25% of test area.
	44.0	—	—	68	102	113	—	—	—	—	120	Basecoat pitted throughout eroded area. Material removed down to prime over 20% of test area.
M313 plus BMS 10-60 Unexposed	28.0	—	50	61	86	—	—	—	—	—	150	Basecoat smooth, except pieces lost from 15% of eroded area. No primer showing.
	27.0	30	—	50	61	150	150	—	—	—	150	Basecoat severely eroded and pitted equaling 30% of test area. Material peeled down to primer 0.95 x 0.95 cm beyond eroded area.
M313 plus BMS 10-60 7-day Skydrol spillage	35.0	—	—	68	74.3	—	—	—	—	—	180	Basecoat smooth and uniform. Little erosion observed. Five small pit marks randomly located. No primer showing.
	35.0	—	—	—	68	—	—	—	—	—	180	Basecoat smooth and not severely eroded, except for material loss at one end equaling 5% of test area. No primer showing.
Astrocoat plus BMS 10-60 Unexposed	Run at 224 m/s (500 mph) for 2.5 min	—	—	—	8.8	60	60	—	—	—	60	Basecoat smooth and glossy. Pitting, peeling, and material loss equal to 25% of test area. Top-coat peeled beyond eroded area.
	Run at 224 m/s (500 mph) for 2.2 min	—	—	—	9.0	34	60	—	—	—	60	Basecoat severely pitted and material removed from 40% of test area. Coating peeled down to primer beyond eroded area.
Astrocoat plus BMS 10-60 7-day Skydrol spillage	10.2	—	—	—	20	180	—	—	—	—	180	Basecoat smooth and glossy. Peeled 0.48 x 2.54 cm at one end.
	20.0	—	—	—	30	180	—	—	—	—	180	Basecoat smooth, glossy, and uniform. Two small pit marks at one end.
B-274, no topcoat Unexposed	—	—	—	—	—	—	—	—	—	—	180	No erosion. Surface slightly dulled.
B-274, no topcoat 2-day Skydrol spillage	—	—	—	—	—	—	—	—	—	—	180	No erosion. Surface slightly dulled.
	—	—	—	—	—	—	—	—	—	—	180	No erosion. Surface slightly dulled.
	—	—	—	—	—	—	—	—	—	—	180	No erosion. Surface slightly dulled.

[a]Removal down to basecoat. [b]Removal down to primer.

Table A-7. Rain Erosion Test Results—224 m/s (500 mph)

Configuration	Penetration time (min)										Total test time (min)	Post-test condition of specimen
	Percent topcoat removed[a]					Percent basecoat removed[b]						
	Initial	25	50	75	100	Initial	25	50	75	100		
B-274 plus BMS 10-60 Unexposed	9.0	–	–	–	19	76.9	–	–	–	–	76.9	Basecoat pitted throughout eroded area. Material removed down to primer equaling 20% of test area.
	7.0	–	–	–	19	50	–	–	60	76.9	76.9	Basecoat removed down to primer or base metal on 100% of test area. Removal of the material appeared to be in pieces.
B-274 plus BMS 10-60 7-day Skydrol spillage	7.5	–	–	20.3	25	48	80	–	–	–	80	Basecoat severely pitted throughout test area. Material removed down to primer in 30-40% of test area.
	9.4	–	–	20.3	25	74	85	110	–	–	110	Basecoat severely pitted throughout test area. Material removed down to primer on 60% of test area.
M313 plus BMS 10-60 Unexposed	6.5	–	11	–	22	–	–	–	–	–	170	Basecoat smooth and uniform. Not severely eroded except for small amount of material (equaling 5% of test area) removed from one end.
	6.5	–	11.5	–	22	54	54	54	54	54	60	Basecoat roughed in eroded area. Coatings peeled down to primer on 50% of entire specimen.
M313 plus BMS 10-60 7-day Skydrol spillage	1.5	–	–	–	10.5	–	–	–	–	–	180	Basecoat smooth and glossy. Four localized pieces of material removed. No primer showing.
	1.0	–	–	–	7	–	–	–	–	–	180	Basecoat smooth and glossy. Single piece of material removed 0.16 x 0.48 cm. No primer showing.
Astrocoat plus BMS 10-60 Unexposed	2.9	5.0	7.2	–	10	60	–	–	–	–	90	Basecoat pitted throughout eroded area and peeled well beyond eroded area. Peeled area (not down to primer) equal to 80% of test area. Specimen had appearance of basecoat delamination.
	2.7	5.0	7.5	–	10	32	44	60	–	–	90	Basecoat severely eroded and peeled down to primer on 50% of entire specimen.
Astrocoat plus BMS 10-60 7-day Skydrol spillage	2.2	–	–	–	15	64	80	–	–	–	110	Basecoat pitted throughout eroded area. Basecoat peeled beyond normal erosion area. Peeled area (not down to primer) equal to 50% of test area. Specimen had appearance of basecoat delamination.
B-274, no topcoat Unexposed	2.1	–	–	–	18	77	–	110	–	–	110	Basecoat peeled down to primer equal to 50% of test area. Peeled area extended well beyond eroded area.
	–	–	–	–	–	–	–	–	–	–	180	No erosion. Only slightly dulled surface.
	–	–	–	–	–	43	–	–	–	–	100	No erosion except for 0.64 x 1.27 cm piece of material removed down to primer. Surface slightly dulled.
B-274, no topcoat 2-day Skydrol spillage	–	–	–	–	–	–	–	–	–	–	180	No erosion, only slightly dulled surface.
	–	–	–	–	–	73	–	–	–	–	180	No erosion except for one 0.64 x 1.91 cm piece of material removed down to base metal. Only slightly dulled surface elsewhere.

[a]Removal down to basecoat. [b]Removal down to primer.

Table A-8. Film Peel Strength

Film	Adhesive	Control specimen (no immersion)		24 hr (water immersion)		24 hr (Skydrol immersion)	
		kg/cm	(lb/in)	kg/cm	(lb/in)	kg/cm	(lb/in)
Tradlon	Essex Chemical 23-700	0.0[b]	(0.0)[b]	Not tested[a]		0.04	(0.25)
	Isochem UE25	0.12	(0.7)	Not tested[a]		0.27	(1.5)
	H. B. Fuller UR2139	0.18	(1.0)	0.23	(1.3)	0.27	(1.5)
	Cal Polymers 1900	0.04	(0.25)	0.04	(0.25)	0.05	(0.3)
	H. B. Fuller FE 1402	1.14	(6.4)	1.46	(8.2)	1.75	(9.8)
	Essex Chemical Pro Seal 899	0.80	(4.5)	1.20	(6.7)	1.57	(8.8)
	Tra-Con 2133	0.86	(4.8)	0.55	(3.1)	0.34	(1.9)
	B. F. Goodrich A-1186-B	0.36	(2.0)	0.41	(2.3)	0.84	(4.7)
Kynar	Essex Chemical 23-700	Not tested[a]		Not tested[a]		Not tested[a]	
	Isochem UE25	Not tested[a]		Not tested[a]		Not tested[a]	
	H. B. Fuller UR2139	Not tested[a]		Not tested[a]		Not tested[a]	
	Cal Polymers 1900	Not tested[a]		Not tested[a]		Not tested[a]	
	H. B. Fuller FE 1402	1.34	(7.5)	1.66	(9.3)	1.50	(8.4)
	Essex Chemical Pro Seal 899	Not tested[a]		Not tested[a]		Not tested[a]	
	Tra-Con 2133	2.86	(16.0)	(3.28)	(18.4)	3.27	(18.3)
	B. F. Goodrich A-1186-B	Not tested[a]		Not tested[a]		Not tested[a]	
Kapton	Essex Chemical 23-700	0.0[b]	(0.0)[b]	0.02	(0.1)	0.05	(0.3)
	Isochem UE25	0.54	(3.0)	0.66	(3.7)	0.80	(4.5)
	H. B. Fuller UR2139	1.00	(5.6)	0.55	(3.1)	0.98	(5.5)
	Cal Polymers 1900	0.32	(1.8)	0.34	(1.9)	0.23	(1.3)
	H. B. Fuller FE 1402	1.04	(5.8)	(1.21)	(6.8)	1.30	(7.3)
	Essex Chemical Pro Seal 899	0.82	(4.6)	1.48	(8.3)	1.41	(7.9)
	Tra-Con 2133	1.0	(5.6)	1.30	(7.3)	0.79	(4.4)
	B. F. Goodrich A-1186-B	0.37	(2.1)	0.64	(3.6)	0.48	(2.7)
UHMW Polyolefin	Film contains pressure sensitive adhesive backing	1.39	(7.8)	1.73	(9.7)	1.66	(9.3)

[a]Specimens not tested due to blistering of film or debond.

[b]Film too weak to measure.

APPENDIX B
FLIGHT SERVICE EVALUATION SUMMARY—CONTINENTAL AIRLINES

A letter from Continental Airlines to the Contractor summarizes the user evaluation of coatings flown for 14 months on Air Micronesia 727 N18479. The letter refers to coating condition as a function of time. Figure B-1 correlates time to flight hours and landings actually accumulated during the flight service evaluation.

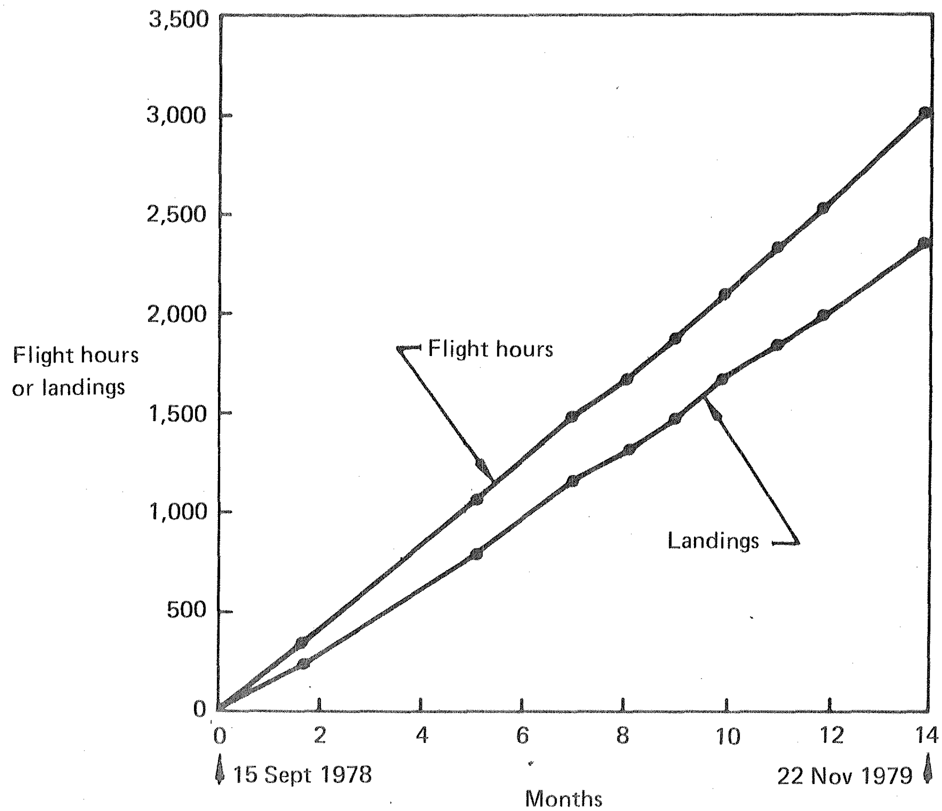

Figure B-1. Coating Evaluation—Flight Hours and Landings

CONTINENTAL AIRLINES

7300 WORLD WAY WEST
LOS ANGELES INTERNATIONAL AIRPORT
LOS ANGELES, CALIFORNIA 90009

PHONE (AREA 213) 646 2810
CABLE CONAIR USA
TELEX 06 74402

A10 : 56

December 7, 1979

727/57.00

Boeing Commercial Airplane Company
P.O. Box 3707
Seattle, Washington 98124

Attention: Mr. R. L. Kreitinger,
Task Manager

Subject: Service Evaluation Summary - Leading Edge Rain Erosion Protection Boeing 727 Aircraft N18479

Dear Mr. Kreitinger:

In late summer of 1978, the Boeing Company contacted Continental regarding the possibility of arranging an in-service evaluation of several rain erosion protective coating systems on an Air Micronesia 727 aircraft. By mutual agreement a service evaluation program was developed and two products were applied to the leading edges of the slats and horizontal stabilizer of aircraft 727-92C N18479 in early September. The #1, 2, 3 and 4 slats and the left horizontal stabilizer leading edges were coated with Caapcoat B274. The #5, 6, 7 and 8 slats and the right horizontal stabilizer leading edges were coated with Chemglaze M313. Material and application instructions were accomplished in accordance with Continental Airlines Engineering document E.A. 551A012.

The coating systems were applied by Continental Paint Shop personnel with no unusual difficulty and without the benefit of temperature or humidity control. Some edge tearing was experienced with the Caapcoat when removing the masking tape indicating either a material adhesion problem, poor surface preparation or both. A deviation to the preparation process and primer material was accomplished on slat #2 and #7 in an effort to improve adhesion properties.

The aircraft returned to Air Micronesia service on September 15, 1978, providing the initial baseline for a fourteen month service evaluation of the coating systems. During this period the aircraft accumulated in excess of 2,200 landings and 2,800 flight hours operating exclusively under the severe rain erosion and coral impact damage environment inherent with the Micronesia route structure. Also, the service evaluation was conducted without benefit of any maintenance touch-up or refurbishment of the coatings due to foreign object impact damage or deterioration.

During the first six months of operation, no concernable deterioration of the coatings were noted. After nine months most of the coatings remained intact, however, some minor deterioration was observed. After eleven months, moderate deterioration (spotting and peeling) was noted on several slats. At this point a large area peeled off the outboard end of the #2 slat and spotting was noted on the #5 and #6 slats. Small areas of peeling were noted near the ends of #3 and #4 slats. The horizontal stabilizer showed very little signs of deterioration. By the end of the evaluation the deterioration rate increased significantly in those areas where prior deterioration had been observed.

The service evaluation indicates the tested materials (Caapco B-274 and Chemglaze M313) will provide leading edge protection without maintenance care for at least six months. After six months some maintenance will be required (repairs and refurbishment) in order to maintain the coatings in an aerodynamically smooth serviceable condition. Total recoating may be required between twelve and eighteen months on aircraft operating in a severe rain erosion environment.

Sincerely yours,

CONTINENTAL AIRLINES

D. L. Parks

D. L. Parks
Manager, Structures Engineering

DLP:nf

cc: J. R. Kightlinger

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15. Supplementary Notes

Technical Monitor: D. B. Middleton
NASA Langley Research Center

16. Abstract

A previous study, reported in NASA CR 158954, identified 3 liquid coatings and 4 films that might improve and/or maintain the smoothness of transport aircraft surfaces. Laboratory tests were performed on the liquid coatings (elastomeric polyurethanes) exposed to synthetic type hydraulic fluid, with and without a protective topcoat. Results were analyzed of a 14-month flight service evaluation of coatings applied to leading edges of an airline 727. Two additional airline service evaluations were initiated. Laboratory tests were conducted on the films, bonded to aluminum substrate with various adhesives, to determine the best film/adhesive combinations.

A cost/benefits analysis was performed and recommendations made for future work toward the application of this technology to commercial transports.

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